Looking for milli-charged particles with a new experiment at the LHC

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We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3}e - 10^{-1}e$ for masses in the range $0.1 - 100$ GeV, which is the least constrained part of the parameter space for milli-charged particles. This is a new window of opportunity for exploring physics beyond the Standard Model at the LHC.

With no clear evidence for the existence of grand unification or magnetic monopoles, the quantization of charge remains a mystery [1]. The search for a non-quantized charged particle, commonly known as a milli-charged particle (mCP), progressed through the efforts of many direct experiments and indirect observations over many years [2–6]. The parameter space spanned by the mass and charge of the mCPs is strongly constrained by direct searches from accelerator experiments [3–6] and indirect observations from astrophysical systems [2, 3, 7, 8], the cosmic microwave background [9], big-bang nucleosynthesis [10], and universe over-closure bounds [2].

While direct laboratory searches robustly constrain the parameter space of mCPs, indirect observations can be evaded by adding extra degrees of freedom. In particular, the parameter space for mCPs with masses $M_{mCP} < 100$ GeV is largely unexplored by direct searches.

In this Letter we propose a new search to be conducted at the LHC with a dedicated detector targeting this unexplored part of parameter space, namely mCPs with masses $0.1 < M_{mCP} < 100$ GeV, for charges $Q$ at the $10^{-3}e - 10^{-1}e$ level. The experimental apparatus would be one or more roughly 1 m$^2$ scintillator detector layers positioned near one of the high-luminosity interaction points of the LHC, such as ATLAS or CMS. The experimental signature would consist of a few photo-electrons (PE) arising from the small ionization produced by the mCPs that travel unimpeded through material after escaping the ATLAS or CMS detectors. Moreover, the experiment proposed is a model-independent probe on mCPs, since it relies only on the production and detection of mCPs through their QED interactions.

We base the estimates for the potential reach of our proposed experiment on a particular theoretical framework, which we now briefly describe. While it is possible to simply add mCP particles to the Standard Model (SM), this is both unappealing from a theoretical point of view as well as strongly constrained by early universe over-production of these particles (see [2, 3, 10, 11] and references therein). A more appealing possibility is the existence of an extra abelian gauge boson that is kinetically mixed with the hypercharge of the SM as in the original work of Holdom [12]. Any new matter that is charged under this abelian gauge symmetry then couples as a mCP to the SM. This scenario also avoids the problem of over production in the early Universe because the mCP can annihilate to the massless gauge boson and deplete [10, 13].

The simplest realization of this setup is a model with a single extra abelian gauge field that couples to a massive Dirac fermion ("dark QED") and that mixes with the cosmic microwave background [9], big-bang nucleosynthesis [10], and universe over-closure bounds [2].

The coupling of the mCP to the photon and $Z^0$ boson, even when these heavy fields are not accessible at low energies. The experimental apparatus would consist of a few photo-electrons (PE) arising from the small ionization produced by the mCPs that travel unimpeded through material after escaping the ATLAS or CMS detectors. Moreover, the experiment proposed is a model-independent probe on mCPs, since it relies only on the production and detection of mCPs through their QED interactions.

The new matter field $\psi$ is a Dirac fermion of mass $M_{mCP}$ that is charged under the new $U(1)$ field $A'_\mu$ with charge $e'$, and the field-strength is defined as $A'_{\mu\nu} = \partial_\nu A'_\mu - \partial_\mu A'_\nu$. The last term in Eq. (1) is a kinetic mixing term between the field strength of the new gauge boson and that of hypercharge. Such a term is expected in grand unified theories and more generally whenever there exists massive fields that are charged under both hypercharge and the new gauge boson, even when these heavy fields are not accessible at low energies.

We can eliminate the mixing term by redefining the new gauge boson as, $A'_\mu \rightarrow A'_\mu + \kappa B_\mu$. Applying this shift the mixing term cancels and the kinetic term of $B_\mu$ receives an overall contribution of $\kappa^2$ that simply defines the hypercharge coupling. More importantly, this field redefinition results in a coupling of the charged matter field $\psi$ to hypercharge,

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i \bar{\psi} \left( \partial + i e' A' - i \kappa e B + i M_{mCP} \right) \psi$$

The new matter field $\psi$ therefore acts as a field charged with a charge $\kappa e'$, a milli-charge [12]. The coupling of the mCP to the photon and $Z^0$ boson is determined by the SM decomposition of hypercharge as $B_\mu = \cos \theta_W A_\mu - \sin \theta_W Z_\mu$. Therefore $\psi$ couples to the photon and $Z^0$ boson with a charge $\kappa e' \cos \theta_W$ and $-\kappa e' \sin \theta_W$, respectively. The fractional charge in units of the electric charge is therefore $\epsilon = \kappa e' \cos \theta_W / e$. 

In previous decades, considerable experimental effort has been dedicated to exploring the parameter space of mCPs [2, 3, 7, 8, 10, 11, 14]. The constraints come from a variety of direct laboratory searches and indirect astrophysical and cosmological observations. While strong indirect bounds exist in the GeV−TeV range for mCPs charged under QED only, these bounds essentially disappear when a new massless \( U(1) \) is added, as in Eq. 1. In Fig. 1 we show the general constraints on mCPs in this scenario [10], together with the projected sensitivity associated with the current proposal.

We begin with constraints on the present-day abundance of mCPs from production in the early Universe. For the range of couplings relevant for this proposal, the mCP particles are in thermal equilibrium with the rest of the SM. The dark QED sector therefore has the same temperature as the rest of the SM. However, as the Universe cools, the number density of mCP is exponentially depleted through pair annihilation in the dark sector. This process can be sufficiently efficient to avoid constraints on relic abundance of the mCP. For example, with \( e' = 0.3 \) and \( M_{mCP} = 1 \) GeV, the relic density is \( 10^{-5} \) that of dark matter. Even smaller relic densities are expected for a larger dark charge or if more annihilation channels are open. Another constraint comes from the number of relativistic degrees of freedom, known as \( N_{\text{eff}} \), on the massless dark photon. However, since the dark photon decouples together with the mCP it will be much colder than the rest of the SM after entropy injection at later times. Since the contribution to \( N_{\text{eff}} \) scales like the fourth power of the temperature, this contribution is negligible when decoupling happens above a GeV or so. See refs. [10, 13, 15] for a very detailed recent analysis.

Laboratory experiments have placed the strongest direct limits on mCPs for \( 10^{-5} \lesssim \epsilon \lesssim 10^{-3} \) over the range \( M_{mCP} < 300 \) GeV. These constraints are the result of dedicated searches at beam-dump experiments [4], decays of ortho-positronium [5], as well as free-quark searches, trident process searches, and the measurement of the invisible width of the \( Z^0 \) boson [3]. A recent analysis looking for low ionizing particles in CMS excluded particles with charge \( \pm e/3 \) for \( M_{mCP} < 140 \) GeV and particles with charge \( \pm 2e/3 \) for \( M_{mCP} < 310 \) GeV [5].

Two other possible new probes of mCPs with \( M_{mCP} \gtrsim 1 \) GeV are cosmic rays and B-factories. We verified that the flux of mCPs originating from cosmic rays is negligible for detection at either surface or underground experiments. As for B-factories, these offer two generic classes of searches with potential sensitivity. First, searches for tagged mesons decaying invisibly (for example \( \Upsilon(1s) \to \gamma \) invisible) could be sensitive to the process \( b\bar{b} \to \psi \bar{\psi} \), where the \( \psi \)'s are registered as missing energy. However, the sensitivity of these analyses is relatively weak [16]. In particular, we find \( Q < 0.23e \) for \( M_{mCP} < m_{\Upsilon(1s)}/2 \). Another possibility is the continuum process \( e^+e^- \to \gamma \psi \bar{\psi} \). We recast the results from the BaBar search for the untagged decay \( \Upsilon(3S) \to \gamma A^0 \), with \( A^0 \) an invisibly decaying scalar [17].

The analysis consists of a bump-search in the observable \( m_A^2 \equiv m_{\Upsilon(3S)}^2 - 2E_\gamma^2 m_{\Upsilon(3S)} \), where \( E_\gamma^2 \) is the photon energy in the centre-of-mass frame. Because the analysis is a bump search the sensitivity achieved by simply recasting the results to the milli-charge continuum process was found to be sub-optimal: at a mass of \( M_{mCP} = 0.1 \) GeV the mCP’s charge is only constrained to be less than \( 0.1e \) and the bound deteriorates quickly to as high as \( 0.5e \) at \( M_{mCP} = 0.5 \) GeV.

We now turn our discussion to the LHC, which offers a unique target of opportunity for model-independent searches for mCPs in the \( 0.1-100 \) GeV range. First we address the production mechanism for mCPs, followed by a discussion of the experimental setup for detection. The main production channel at hadron colliders for mCPs in the GeV mass range is through the Drell-Yan process. We show the production cross section for mCPs in “dark QED” in Fig. [2]. Run2 of the LHC is expected to run at instantaneous luminosities up to \( \mathcal{L} \approx 2 \times 10^{34} \) cm\(^{-2}\)s\(^{-1}\). As such, for a charge of \( 10^{-2}e \), already with several fb\(^{-1}\) one is faced with tens to thousands of mCPs produced in the mass range of \( \mathcal{O}(1-100) \) GeV. We simulated the mCPs Drell-Yan signal in MADGRAPH5 [19], where they can be produced through an s-channel \( \gamma \) or \( Z^0 \), after implementing our own model where we added a new fermion to the SM charged under hypercharge only, as in Eq. (2). Fig. [2] shows the production cross section for mCP pairs with combined invariant mass greater than 2 GeV, the lowest momentum transfer where PDFs have
We used the “dark QED” model section is after requiring the invariant mass of the mCP pair to be greater than 2 GeV. We used the “dark QED” model of Eq. (2), where an additional enhancement is obtained for $M_{mCP} < m_{Z}/2$ due to the $Z^{0}$-mediated contribution. The Drell-Yan cross section includes an overall normalization from NNLO corrections obtained from VRAP. The $Υ(1_{s}) \rightarrow ψ\bar{ψ} + X$ cross section includes $y_{Υ(1s)} < 2.5$ and $p_{T,Υ(1s)} > 2 GeV$. The $J/ψ \rightarrow ψ\bar{ψ} + X$ is shown after requiring $y_{J/ψ} < 2.5$ and $p_{T,J/ψ} > 6.5$ GeV. Assuming the same $p_{T}$ cut on the jet, the cross section for $\bar{ν}ν + 1j$ through the $Z^{0}$ boson is $\sim 3.5$ pb at 14 TeV. This background alone would require an integrated luminosity of greater than 300 fb$^{-1}$ to yield a $S/B \sim$ a few for $Q = 0.1e$. Additionally, the small $S/B \sim 10^{-4}$ means that more data will not necessarily improve the sensitivity as the analyses become systematics-dominated. Thus, to detect mCPs at the LHC, an alternative experimental strategy is likely needed.

We propose a dedicated experiment to search for mCPs in which one or more small (1 m$^{3}$) scintillator layers are deployed sufficiently near one of the high-luminosity LHC interactions points, i.e., ATLAS/CMS, such that a detectable fraction of the flux of mCPs produced in the $pp$ collisions provided by the LHC would be intercepted by the experimental apparatus. The rapidity distribution in the lab frame extends to high values even for $M_{mCP} \sim 50$ GeV. The fraction of events with at least one mCP in the rapidity range $|y| < 1$ for $M_{mCP} = 1.5, 10$ and 50 GeV is 12%, 19%, 23%, and 27%, respectively. Given the expected rapidity distribution, better coverage would be obtained by placing the detector as much in the forward region as possible. At the same time, since the flux generally drops with the square of the distance one would like to place the detector as close as possible to the pp interaction point of either ATLAS or CMS.

A mCP detector must be shielded from the ionizing radiation produced by SM particles emanating from the proton beams and their interactions. Because a mCP detector will necessarily be designed to be sensitive to extremely small ionization energy depositions, any $Q = 1e$ particle entering the detector will flood it with photons for up to several $μs$, during which no mCP signal could be seen. The large flux of such particles within the ATLAS/CMS experimental caverns, therefore, rules out placement of a mCP detector there. Moreover, even if it were a suitable environment, there is no sufficient space available in the already crowded forward regions of these experiments. One possibility would be to locate detectors on the surface, roughly 100 m above the interaction point. Another more advantageous possible location would be to use the counting room adjacent to the experimental cavern, typically located underground and about 20 m from the interaction point. For instance, USA15, near ATLAS, is a large cavern housing computing and trigger electronics shielded by a 2 m thick concrete wall that reduces radiation to less than a few $μSv/h$ [23], only about 10 times the normal environmental background rate. A similar environment exists in USC55, near CMS. An advantage of the low-radiation requirement of the counting rooms is that access to these experimental areas is possible during running beam conditions. The acceptance of a 1 m$^{2}$ detector at such a location 20 m away would be about 0.01% for $M_{mCP} \sim$ few GeV.

A $Q = 1e$ minimum-ionizing charged particle leaves roughly 2 MeV/cm in a material of density 1 g/cm$^{3}$ [24]. For plastic scintillator, such energy deposition results in about $10^{4}$ photons per MeV, meaning $2 \times 10^{6}$ photons

![Graph](image-url)
would be liberated in a 1 m long scintillator. For a particle with electric charge $Q < 1e$, the energy deposition is reduced by the factor of $Q^2$ mentioned above, resulting in just a few photons liberated on average in the same 1 m long scintillator. Allowing for an estimated detection efficiency of about 10%, we can therefore expect an average of one PE via an attached phototube for each mCP with $Q = 2 \times 10^{-3}e$ that traverses a standard length of 140 cm plastic scintillator [4]. The signal to search for then is one or more PEs.

Similar to Ref. [4], 140 \times 10 \times 5 \text{ cm}^3 plastic scintillator bars could be used, with an associated phototube and readout for each bar. 200 such bars would be needed to cover 1 m$^2$ of area perpendicular to the beam-line, with each mCP passing through the 140 cm length of a bar. The time resolution of such scintillators is sufficiently good ($\approx 5$ ns) that background can be measured during gaps within the accelerator bunch structure (such as the abort gap), as well as in beam-off periods. Since the background rate for single PE pulses from dark-current, noise, and background radiation is expected to be relatively large (about 100 Hz to 1 kHz depending on the quality of the detector elements used), we propose to add extra layers of scintillators to form coincidences with a signal in the corresponding bar of the first layer within a narrow time window ($\approx 5$ ns). Muons from either pp collisions or cosmic rays could be vetoed if more than a few PE are deposited. Furthermore, by inverting this veto, these same muons could be used to align and time-in the experimental apparatus. They would also provide a “standard candle” against which PE depositions could be compared.

We now estimate the dark-current background rate, which we expect to be the dominant background contribution if a search for mCPs were carried out with the experiment we are proposing. Additional background from activity in the scintillator, due to background radiation and subsequent photo-multiplier afterpulsing, may also contribute significantly, but can hopefully be reduced to manageable levels with additional shielding, detector optimization, and pulse-shape discrimination. This will have to be studied with small-scale detector tests in situ. We assume rates of 550 Hz, 94 Hz, 12 Hz, and 10 Hz for $N_{\text{PE}} \geq 1, N_{\text{PE}} \geq 2, N_{\text{PE}} \geq 3, N_{\text{PE}} \geq 4$, respectively in a single PMT, obtained from Fig. 65 of Ref. [25]. Assuming an instantaneous luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$, and a trigger live-time of $1.5 \times 10^5$ s, we can expect $\sim 10^{10}$ background events in 300 fb$^{-1}$ for one or more PE in a single PMT. With 200 bars needed to cover the 1 m$^2$ of area discussed above, the total background would be $\sim 10^{12}$ events in 300 fb$^{-1}$, expected to be delivered by 2022. For 3000 fb$^{-1}$, since it will be delivered with an instantaneous luminosity $1 \times 10^{35}$ cm$^{-2}$s$^{-1}$ the live-time will only increase by a factor of 2 and the expected background contribution would remain $\sim 10^{10}$ for one or more PE in a single PMT. Additional discrimination can be achieved by adding two more layers of scintillators and requiring coincident PE hits. Assuming 5 ns timing resolution for the PMTs, requiring a coincidence in the second layer would reduce the background to $10^6$ coincident events with $N_{\text{PE}} \geq 1$ in a PMT pair of back-to-back scintillator bars. Requiring triple-incidence by adding a third layer would then bring the background to $O(10)$ events with $N_{\text{PE}} \geq 1$, at the cost of a moderate loss in signal efficiency. It is possible that the slewing of small signals and/or time-of-flight differences for photons within the scintillators could degrade the timing resolution to $\sim 10$ ns, but even in this scenario the total background contribution would only increase by a factor of $\sim 4$ when triple-incidence is required. The experimental setup with three layers is illustrated in Fig. 3.

In Fig. 1 we show the estimated 95\% C.L. exclusion and 3\% sensitivity of our proposal, assuming a detector composed of three 1 m$\times$1 m$\times$1.4 m layers positioned 45$^\circ$ away from the beam-axis. Each layer would be composed of 200 scintillator bars, and the mCP signal is one or more PE at each of the three layers within a small $\approx 5$ ns window of each other. This setup could be realized if the detector is placed in either of the counting rooms at ATLAS or CMS. We estimate the signal detection efficiency by estimating the Poisson probability that a mCP signal leaves one or more PE. The average number of PE deposited by a mCP is given by $\lambda = (Q/e)/(2\times10^{-3})$ [4]. Though the Lorentz force on a mCP due to the magnetic field at either ATLAS or CMS is suppressed by $Q$, we estimate that it would produce a $O(0.1 \text{ to } 100)$ cm deviation in their trajectory over 20 m for $Q = (0.001 \text{ to } 0.1)e$ and a momentum of $10 \text{ to } 100$ GeV; we have neglected this effect in the calculation of the signal acceptance.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{A schematic showing the experimental setup proposed in this work. Three 1 m$\times$1 m$\times$1.4 m scintillators, each composed of 200 10 cm$\times$5 cm$\times$140 cm bars could be deployed in either the ATLAS or CMS counting room. The mCP signal would consist of one or more photo-electrons deposited by the mCP, as it travels through each of the three detector layers, within a narrow timing window from each other.}
\end{figure}
In this Letter we proposed a model-independent search for mCPs, which will extend sensitivity in the mass range $0.1 \lesssim M_{mCP} \lesssim 100$ GeV by up to two orders of magnitude in electric charge over previous experiments. We estimated the potential sensitivity of this experiment to the particular realization of mCPs in “dark QED”. The experimental setup requires a new small-scale scintillator detector nearby one of the high-luminosity interaction points at the LHC, i.e. ATLAS or CMS. Such a detector seems feasible to build for a reasonable cost with existing technology, and its placement would not interfere with existing scientific operations at the LHC.

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