Probing millicharged particles with NA64 experiment at CERN

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Abstract

In this note we estimate the sensitivity of the NA64 experiment currently searching for dark sector particles in missing energy events at the CERN SPS to millicharged particles ($\chi$). We consider searches with the $\simeq 100$ GeV electron and muon beams and show that the later one allows to obtain more stringent bounds on the millicharge $Q_\chi$, which for the $\chi$ masses $100 \text{ MeV} \leq m_\chi \leq 500 \text{ MeV}$ at the level $Q_\chi/e \lesssim O(10^{-3}) - O(10^{-2})$.

1 Introduction

The millicharged particles ($\chi$), i.e. particles with an electric charge $Q_\chi = \epsilon e$ much smaller ($\epsilon \ll 1$) than the elementary charge $e$, have been considered long ago. They were discussed in connection with the mechanism of the electric charge quantization and a possible nonconservation of the electric charge [1]. In the context of grand unification models this mechanism may be linked to magnetic monopole and electric charge quantization [2]. However, the magnetic monopoles have not been observed yet, and the underlying mechanism for charge quantization remains non confirmed, thus making searches for millicharged particles of a great interest.

The $\chi$s have been also proposed in various extensions of the Standard Model (SM). In particular, in the hidden (dark) sector models with a new $U'(1)$ gauge group [3], see also [4]. In this scenario the kinetic mixing between the $U'(1)$ and the SM fields is described by a term $\frac{1}{2} F'_{\mu\nu} F'^{\mu\nu}$. Where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ with $A'_\mu$ and $A_\mu$ being a dark photon and ordinary photon respectively. After a redefinition of the hidden vector field $A'_\mu \rightarrow A'_\mu + \epsilon A_\mu$ one can find that electromagnetic field $A_\mu$ interacts with hidden fermions of dark sector, namely $L_{\text{int}} = \epsilon A_\mu J^\mu_D$. Here $J^\mu_D$ is the $U'(1)$ current of fermions, $J^\mu_D = g_D \tilde{\chi} \gamma^\mu \chi$ for spin 1/2 fermions. This means that the dark sector particles $\chi$ interact with the photon via the effective coupling $Q_\chi = \epsilon g_D$. In this scenario the dark photon remains massless and interacts only
with dark sector particles. In the rest of this work, we will consider the following Lagrangian for the $\chi$s interacting with the electromagnetic field $A_\mu$, assuming that they are spin $1/2$ fermions:

$$\mathcal{L} \supset i\bar{\chi}\gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi}\chi + Q_\chi A_\mu \bar{\chi}\gamma^\mu \chi.$$ \hspace{1cm} (1)

where $m_\chi$ is a Dirac mass of the hidden particles.

As it follows from (1) in the leading order the $\chi$ production rate is proportional to $Q_\chi^2$ and the $\chi$s can be effectively produced in any electromagnetic reactions if it is kinematically allowed [5]. The numerous constraints on $Q_\chi$ obtained from the performed beam-dump [6, 7], positronium [8] and reactor [9, 10] experiments, see Ref. [11] for a review, as well as the expected limits from the $e^+e^-$ colliders and the LHC [13, 14] have been reported. Stringent constraints can also be obtained from cosmological and astrophysical considerations, see e.g. [15, 16, 17, 11, 18, 19, 20, 21].

The millicharged particles with $Q_\chi \ll e$ typically escape the detection in an experiment$^1$, because their ionisation energy loss is $\sim Q_\chi^2$ and thus is very small. Therefore, to observe them directly a large number of particles on target is required, see e.g. [7, 12]. However, possible indirect observation of $\chi$s at the fixed-target facilities can utilise another more effective approach - the search for the $\chi$s in missing energy/momentum events [22, 23, 24].

Consider the NA64 experiment at CERN [23, 25, 26, 27], which was designed the search for the light dark matter particles in the reaction of dark photon production $eZ \to eZA'$ followed by the invisible decay of dark photon into hidden states, $A' \to invisible$. It is obvious, that the missing energy signature for the search of dark photons can also be implemented to search for the millicharged particles produced in the similar reaction $eZ \to eZ\chi\bar{\chi}$. At present NA64 experiment uses the electron beam with the energy $E_e \approx 100$ GeV, but there are also plans to use the high intensity muon M2 beam line at the Super Proton Synchrotron (SPS) at CERN [28]. Furthermore, the missing momentum experiments with muon beams at CERN [29, 30, 31] and FermiLab [32, 33] have been proposed recently in order to probe $(g-2)_\mu$ anomaly [34] in the framework of light dark matter sector [24].

It should be noted that the LHC experiments are insensitive to probe sub-GeV dark sector scenario [35] with small coupling constants. In particular, the millicharge parameter space in the ranges $0.1$ GeV $\lesssim m_\chi \lesssim 1$ GeV and $10^{-4} \lesssim Q_\chi/e \lesssim 10^{-3}$ has not been constrained yet by existing experiments. The scenarios of sub-GeV hidden particles can be probed at SHIP [36] proton beam dump facility as well as at MiniBoone [37], DUNE [38] and LSND [39] neutrino detectors. In these experiments the dominant millicharge production are exotic decays

$$\pi^0/\eta \to \gamma\chi\bar{\chi}, \quad J/\psi, \Upsilon \to \chi\bar{\chi}.$$ \hspace{1cm} (2)

The produced millicharged particles elastically scatter on an atomic electrons in the dump, $\chi e \to \chi e$. So the detection of millicharged particles is based on the measurement of low energy electron recoils. The millicharge yield from hadrons [12] is suppressed by both the production term $\sim Q_\chi^2$ and the interaction factor $\sim Q_\chi^4$, such that $N_{\chi\chi} \sim Q_\chi^4$. On the other hand, the number of produced millicharged particles at NA64 is proportional to $Q_\chi^2$ for both electron and muon beams. For muon beam significant gains in millicharge sensitivity compared to electron beam may be achieved by optimizing the active target design of NA64. In particular, $10^{13}$ muons on target are expected to accumulate at NA64 during the couple of months running.

In this note we estimate the discovery potential of millicharged particles search at NA64 experiment for both electron and muon beams. We find that muon beam setup of NA64 provides more stringent bounds on electric charge $Q_\chi$ in comparison with electron beam. The main reason is that 100-GeV electron beam

$^1$Here $e$ is the electron electric charge, $\frac{e^2}{4\pi} = \frac{1}{137}$.
degrades significantly even in the relatively thin lead target of $40X_0$ ($\approx 20 \text{ cm}$) used at NA64. Therefore, the electron missing momentum yield is suppressed by the electron beam struggling factor $X_0$ and the number of produced millicharged particles is proportional to $N_{\chi\chi} \sim X_0$. On the other hand muon radiation length $X_\mu \sim (m_\mu/m_e)^2 X_0 \gg X_0$ and relativistic 100 GeV muons pass through the dump with $L \ll X_\mu$ without significant loss of muon energy. This implies that the millicharge production signal in the muon beam experiment is proportional to the length of the target, $N_{\chi\chi} \sim 40X_0$. Furthermore, one can improve the millicharge sensitivity for the muon beam by increasing the effective interacting length of the active lead target. For instance, by increasing the length of the target by 4 factor of magnitude, one can extend $Q_\chi$ bound by factor 2. This provides an excellent opportunity for NA64 with muon beam to probe wider range of millicharge parameter space. We also derive NA64 bound on millicharges from recent NA64 experimental bound on $\epsilon$ parameter [26] for dark photon model.

The organization of paper is as follows. In next section we collect basic formulae relevant for an estimation of the millicharged particles production rates. In section 3 we present results of our calculations. Last section summarises the main results.

2 Basic formulae for the cross sections

\begin{center}
\begin{tabular}{c c c}
\textbf{Interference $\alpha^{5/2}Q_\chi^3$ - terms} & & \\
\includegraphics[width=0.3\textwidth]{interference}\includegraphics[width=0.3\textwidth]{interference}\includegraphics[width=0.3\textwidth]{interference} & & \\
\textbf{leading $\alpha^3Q_\chi^2$ - terms} & & \textbf{subleading $\alpha^2Q_\chi^4$ - terms} \\
\includegraphics[width=0.3\textwidth]{leading}\includegraphics[width=0.3\textwidth]{leading}\includegraphics[width=0.3\textwidth]{leading} & & \includegraphics[width=0.3\textwidth]{subleading}\includegraphics[width=0.3\textwidth]{subleading}\includegraphics[width=0.3\textwidth]{subleading}
\end{tabular}
\end{center}

Figure 1: Feynman diagrams of millicharge pair production

In this section we present basic formulae for the cross-section of the high-energy lepton scattering on heavy nuclei accompanied by the emission of a bremsstrahlung $\chi\bar{\chi}$ pair

$$ lN \rightarrow lN\gamma^* \rightarrow lN\chi\bar{\chi} \quad (3) $$

with $\chi$ being a millicharged Dirac fermion and $l = e, \mu$. The relevant tree level diagrams are shown in Fig. 1 for muon case. The millicharge emission cross-section (3) is proportional to $\mathcal{O}(\alpha^3Q_\chi^2)$ \(^4\). The differential cross-section $\sigma(lN \rightarrow lN\chi\bar{\chi})$ can be represented in the form [40]

$$ d\sigma(lN \rightarrow lN\chi\bar{\chi}) = d\text{Lips}_{2\rightarrow3} |\mathcal{M}_{2\rightarrow3}|^2 \frac{dk^2}{(2\pi)} \times \chi_{\alpha\beta} $$ \quad (4)

\(^2\)Here $X_0$ is electron radiation length

\(^3\)Here as an estimate we use the length of target for muon experiment $L \sim 40X_0 \approx 20 \text{ cm}$.

\(^4\)We neglect $\mathcal{O}(\alpha^2Q_\chi^4)$ trident millicharge production cross section and relevant $\mathcal{O}(\alpha^{5/2}Q_\chi^3)$ interference terms in our calculations.
where $d\text{Lips}_{2\to 3}$ is Lorentz invariant phase space for a process $lN \to lN\gamma^*$ with off-shell photon in the final state,
\[
|M_{2\to 3}|_{\alpha\beta}^2 = \sum_{\text{spin}} M^{\mu\nu} M^{\nu\mu} g_{\mu\alpha} g_{\nu\beta} \frac{1}{k_{\gamma^*}^4},
\]
and where an averaging over initial lepton spin and summation over outgoing lepton state is performed. The millicharged tensor $\chi_{\alpha\beta}$ has the following form
\[
\chi_{\alpha\beta} = \int \frac{d^3k_1}{(2\pi)^3 2E_1} \frac{d^3k_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^{(4)}(k - k_1 - k_2) \sum j_\alpha j_\beta^*,
\]
with $j_\alpha = Q_\chi\gamma_\alpha \chi$ being a millicharged current, $k \equiv k_{\gamma^*}$ is a total four-momentum of the millicharged pair, $k_{\gamma^*} = k_1 + k_2$. This implies that the millicharge production cross-section $d\sigma(lN \to lN\chi\bar{\chi})$ can be represented in the form
\[
d\sigma(lN \to lN\chi\bar{\chi}) = d\sigma(lN \to lN\gamma^*) \times \frac{Q_\chi^2}{12\pi^2} \frac{dk_{\gamma^*}^2}{k_{\gamma^*}^2} \sqrt{1 - \frac{4m_\chi^2}{k_{\gamma^*}^2}} \left(1 + \frac{2m_\chi^2}{k_{\gamma^*}^2}\right).
\]

Figure 2: Upper limits on the fractional electric charge $Q_\chi/e$ of the hypothetical millicharged fermions of mass $m_\chi$. The areas with the grey shading are the bounds excluded by SLAC [7], collider [43, 44] and EDGES experiment [45, 46]. The projected limits are shown by solid lines. In particular, the expected reaches for SHIP and MilliQuan are taken from [12]. The sensitivity of LDMX is based on MadGraph missing momentum simulation with 16 GeV electron beam on aluminium target [24]. The blue shaded region is the bound experimentally excluded by NA64, see e.g. Ref. [26]. The upper bound at $Q_\chi/e = 0.2$ corresponds to the (90% CL) lower limit on the charge of $\chi$’s above which they are detected in the NA64 HCAL.
The first factor in (7) can be calculated in the equivalent photon approach [41, 42], the corresponding differential cross-section is

$$\frac{d}{dx} \sigma_{2\to3} \approx \frac{2}{3} \frac{\alpha^3 \zeta |k_{\gamma^*}|}{x \bar{u}^2 E_0^2} \left[ m^2 x (-2 + 2x + x^2) - 2(3 - 3x + x^2) \bar{u} \right], \quad x = E_{\gamma^*}/E_0$$

(8)

with $\zeta$ being the photon flux from nucleus

$$\zeta = \int \frac{k_{\gamma^*}^2 + m^2}{k_{\gamma^*}^2/(4E_0^2)} \frac{dt}{t^2} \left[ t - \frac{k_{\gamma^*}^2}{4E_0^2} \right] \frac{Z^2}{a^2} \left( \frac{a^2 t}{a^2 t + 1} \right)^2 \frac{1}{(1 + t/d)^2},$$

(9)

where $a = 111Z^{-1/3}/m_e$ parametrizes the electron screening effect and $d = 0.164A^{-2/3}$ GeV stands to account the finite nuclear size. Such form-factor parametrization (9) accounts for elastic scattering effects only. The inelastic form-factor is proportional to $\sim Z$ and thus can be neglected in high-Z target experiment. The quantities $\bar{u}$ and $|k_{\gamma^*}|$ in (8) are defined by $\bar{u} = -k_{\gamma^*}^2 (1 - x)/x - m^2 x$ and $|k_{\gamma^*}| = (x^2 E_0^2 - k_{\gamma^*}^2)^{1/2}$ respectively. Therefore, one can estimate the $\chi\bar{\chi}$-production rate by integrating (7) over $\gamma^*$ invariant mass

$$\sigma_{lN \to lN\chi\bar{\chi}} \approx \int \frac{dy}{y} \sqrt{1 - \frac{1}{y}} \left( 1 + \frac{1}{2y} \right) \times \frac{Q^2_\chi}{12\pi^2} \times \frac{d\sigma_{2\to3}}{dx},$$

(10)

where we denote $y = k_{\gamma^*}^2/(4m^2_\chi)$ and $y_{\max} = x^2 E_0^2/(4m^2_\chi)$. Here the lower limit in the integration over $x$ corresponds to the following missing energy cut, $E_{\text{miss}}/E_0 \equiv E_{\gamma^*}/E_0 > 1/2$. Numerical analysis reveals that for $m_\chi \gtrsim m_l$ the cross-section (10) can be approximated as

$$\sigma(lN \to lN\chi\bar{\chi}) \approx \frac{4}{3} \frac{\alpha^3 \zeta}{(2m_\chi)^2} \left[ \ln \frac{1}{2} \left( \frac{2m_\chi}{m_l} \right)^2 + \frac{11}{12} \right] \times \frac{Q^2_\chi}{12\pi^2}, \quad \kappa = 0.8.$$  

(11)

with a reasonable accuracy. In addition, we note that (11) generally resembles, up to the numerical factor $\sim Q^2_\chi$ and additive correction to the logarithm, the total cross-section for the dark photon (DP) production [42], in which the dark photon mass is redefined as $m_{\chi'} \to 2m_\chi$. This observation allows one to estimate the expected constraints for the parameter space of the millicharged particles directly for muon beam at NA64.

### 3 Expected bounds on charge $Q_\chi$

In this section we estimate expected bounds on charge of millicharged particles using the results of the previous section. For thin target with $L_T \ll X_l$ the millicharge yield which originates from the $lZ \to lZ\chi\bar{\chi}$ process is

$$N_{\chi\bar{\chi}} = N_{\text{LOT}} \times \frac{\rho \times N_A}{A} \times L_T \times \sigma_{\chi\bar{\chi}},$$

(12)

where $A$ is the atomic weight, $N_A$ is Avogadro’s number, $\rho$ denotes the target density and $\sigma_{\chi\bar{\chi}}$ is the the millicharged pair production cross-section (10).

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5Here $X_l$ is the radiation length for lepton $l = e$ or $\mu$. 
Let us consider the case of muon beam at NA64. In our estimates we assume that the muon beam energy is about 100 GeV and the muon flux is about $N_{MOT} = 5 \cdot 10^{13}$. We consider lead target with thickness of $L_T = 40X_0 = 20$ cm. We neglect muon energy losses in the lead target\(^6\). We assume that the energies of initial and final muons are known\(^7\). The missing energy signature can be used for the search for pair produced millicharged particles in the millicharged production reaction $\mu N \rightarrow \mu N \chi \chi$ in full analogy with the search for dark photon.

Using the formula (12) for the number of produced millicharged particles and the expression (10) for the production cross section, we find the expected bound on millicharge $Q_\chi$.\(^8\) We require $N_{\chi \chi} > 2.3$ that corresponds to 90\% CL exclusion limit on $Q_\chi/e$. In Fig. 2 we show the expected reach of NA64 detector for $N_{MOT} = 5 \cdot 10^{13}$ muons and $N_{EOT} = 5 \cdot 10^{12}$ electrons respectively, we assume that the beam energy is $E_0 = 100$ GeV for both $e$- and $\mu$- modes.

It is instructive to compare qualitatively millicharge limits for muon and electron beam in order to understand why the expected bound from muon setup is enhanced at $m_\chi \gtrsim m_\mu$. Indeed, the ratio of the reaches can be naively approximated as follows

$$\frac{Q_\chi^{(e)}}{Q_\chi^{(\mu)}} \approx \left( \frac{L_{eff}^{(\mu)}}{L_{eff}^{(e)}} \right) \left( \frac{Q_\chi^{(\mu)}}{Q_\chi^{(e)}} \right) \left( \frac{N_{MOT}}{N_{EOT}} \right)^{1/2} \left( \frac{\ln \chi_{\chi}}{\ln \chi_{\chi}} \right), \tag{13}$$

where labels ($\mu/e$) specify a beam type and $L_{eff}$ is the effective length of millicharge lepto-production in the lead target, namely $L_{eff}^{(\mu)} \approx 40X_0$ and $L_{eff}^{(e)} \approx X_0 \approx 0.5$ cm. The latter means that for electron beam the millicharges are essentially produced in the length $L \leq X_0$ of the target due to the large electron energy loss. While the muons produce millicharges uniformly over the whole length of the target. For beam energy $E_0 = 100$ GeV and millicharge masses $m_\chi \gtrsim 200$ MeV the electron and muon cross-sections scale respectively as [42]

$$\sigma_{\chi \chi}^{(e)} \sim \frac{Q_\chi^2}{2m_\chi^2} \left( \ln \frac{1}{2} \left( \frac{E_0}{2m_\chi} \right)^2 + O(1) \right), \quad \sigma_{\chi \chi}^{(\mu)} \sim \frac{Q_\chi^2}{2m_\mu^2} \left( \ln \frac{1}{2} \left( \frac{2m_\chi}{m_\mu} \right)^2 + O(1) \right), \tag{14}$$

where factor 1/2 under the logarithms comes from the integration of production cross-section over the missing energy range, $1/2 < E_{\gamma}/E_0 < 1$. For $N_{MOT} = 5 \cdot 10^{13}$ and $N_{EOT} = 5 \cdot 10^{12}$ one gets $Q_\chi^{(e)}/Q_\chi^{(\mu)} \approx 9$ at $m_\chi = 200$ MeV. This result can be seen from Fig. 2. Indeed, for $m_\chi = 200$ MeV we have $Q_\chi^{(e)}/e \approx 10^{-2}$ and $Q_\chi^{(\mu)}/e \approx 10^{-3}$. One can also estimate the ratio (13) for relatively light millicharges $m_\chi \ll m_\mu$. In this case muons produce the millicharges in the bremsstrahlung-like limit. The cross-sections for both electron and muon beam can be approximated as

$$\sigma_{\chi \chi}^{(e)} \sim \frac{Q_\chi^2}{2m_\chi^2} \left( \ln \frac{1}{2} \left( \frac{2m_\chi}{m_e} \right)^2 + O(1) \right), \quad \sigma_{\chi \chi}^{(\mu)} \sim \frac{Q_\chi^2}{m_\mu^2} \left( \ln \frac{1}{2} \left( \frac{m_\mu}{2m_\chi} \right)^2 + O(1) \right). \tag{15}$$

As a result we get $Q_\chi^{(e)} \gtrsim Q_\chi^{(\mu)}$ for $m_\chi \gtrsim 2$ MeV, see also Fig. 2.

It should be noted that it is possible to link the bound on $e$ parameter for the model with dark photon and bound on the millicharge. Indeed, the interaction of dark photon with the SM particles has the form [42]

$$L_{dark} = \epsilon e J_{SM}^\mu A_\mu^i \tag{16}$$

\(^6\)This approximation is reasonable, because the muon energy struggling reported in [33] is rather small for the beam energy range, $\langle dE_\mu/dz \rangle \approx 12.7 \cdot 10^{-3}$ GeV/cm.

\(^7\)In NA64 facility with muon beam it is assumed to utilize two, upstream and downstream, magnetic spectrometers allowing for precise measurements of momenta for incident and recoiled muons, respectively [29].

\(^8\)We assume background free regime, that looks reasonable, see [29].
where $J_{SM}^\mu = \frac{2}{3} \bar{u} \gamma^\mu u - \frac{1}{3} \bar{d} \gamma^\mu d - \bar{e} \gamma^\mu e + ...$ is the SM electromagnetic current, $\frac{e^2}{4\pi} = \frac{1}{137}$, $A'_\mu$ is the dark photon field and $\epsilon$ is unknown parameter. The goal of the experiments is to derive the bound on $\epsilon$. On the other hand, the bound on $\epsilon$ depends on the dark photon mass $m_{A'}$. The cross-section of dark photon lepton-production $d\sigma(lZ \to lZ A')$ is proportional to the cross section of virtual photon lepton-production, namely

$$d\sigma(lZ \to lZ A') = \epsilon^2 d\sigma(lZ \to lZ \gamma^*).$$

(17)

Here $m^2_{A'} = k^2_{\gamma^*}$, and $k^\mu_{\gamma^*}$ is the four momentum of virtual photon. It follows from Eq. (7) that

$$d\sigma(lN \to lN \chi \bar{\chi}) = \int dm^2_{A'} R(m^2_{A'}, Q^2_{\chi}, m^2_{\chi}) d\sigma(lN \to lN A') \times \frac{1}{\epsilon^2}.$$  

(18)

where

$$R(m^2_{A'}, Q^2_{\chi}, m^2_{\chi}) = \frac{Q^2_{\chi}}{12\pi^2} \frac{1}{m^2_{A'}} \frac{1}{m^2_{\chi}} \left(1 + \frac{2m^2_{\chi}}{m^2_{A'}} \right) \sqrt{1 - \frac{4m^2_{\chi}}{m^2_{A'}}}.$$  

(19)

For the thin target the dark photon yield is determined by the formula (12) with the replacement $\sigma_{\chi \chi} \to \sigma(lZ \to lZ A)$. One can find that for the same target and the same kinematical cuts\(^9\) upper bound $\epsilon_{up}^2(m^2_{A'})$ on $\epsilon^2$ and on $Q^2_{\chi,up}(m^2_{\chi})$ on millicharge $Q_{\chi}$ are related by

$$Q^2_{\chi,up}(m^2_{\chi}) = \left[ \int_{4m^2_{\chi}}^\infty \frac{R(m^2_{A'}, Q^2_{\chi}, m^2_{\chi})}{\epsilon_{up}^2(m^2_{A'})} dm^2_{A'} \right]^{-1}.$$  

(20)

One can show that the formula (20) is valid not only for thin target but also for thick target. Using the formula (20) we can derive experimental bound on millicharges from experimental bound on dark photon $\epsilon$ parameter. For instance, from NA64 experimental bound [26] on $\epsilon_{up}(m^2_{A'})$ we find NA64 bound on $Q^2_{up}(m^2_{\chi})$ on millicharge, see fig. 2.

4 Conclusions

In this note we considered the perspectives of the mill-chaged particles discovery at NA64 experiment at CERN. We have considered both cases of electron and muon beams at NA64 (NA64\(\ e\) and NA64\(\ mu\)). We have found that for $m_{\chi} \geq m_{\mu}$ the use of muon beam will allow to obtain more stringent bounds than the use of electron beam. Moreover, both NA64\(\ e\) and NA64\(\ mu\) will be able to compete with existing experimental data.

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\(^9\)In our case we use cuts $E_{A'} \geq 0.5E_\gamma$ for the dark photon search and cut $E_{\chi} + E_{\bar{\chi}} \geq 0.5E_0$ for the millicharged particles search
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