

Missing energy signatures of inelastic magnetic dipole DM at NA64e

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Some extensions of the Standard Model consider inelastic dark matter (iDM) as an attractive candidate for sub-GeV DM of thermal origin that could be detected at modern accelerators. In the present paper, we calculate the production rate of iDM pairs $\chi_1\bar{\chi}_0$ interacting with the ordinary photon via dipole magnetic moment in the reaction of high-energy electron scattering on nuclei, $e^-N \rightarrow e^-N\chi_1\bar{\chi}_0$, in the NA64e experiment at the CERN Super Proton Synchrotron (SPS). We derive the projected sensitivity of NA64e to such particles assuming $\simeq 10^{13}$ 100 GeV electrons on target. We also show, that incorporating heavy vector meson decays, $\gamma^*N \rightarrow NV(\rightarrow \chi_1\bar{\chi}_0)$, alongside bremsstrahlunglike emission of inelastic dark matter pairs, $e^-N \rightarrow e^-N\gamma^*(\rightarrow \chi_1\bar{\chi}_0)$, will allow NA64e to probe previously unexplored regions of the iDM parameter space, in particular for modest mass splittings, $\Delta \simeq 5 \times 10^{-2}$, and relatively light masses, $m_{\chi_0} \lesssim 100$ MeV.

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I. INTRODUCTION

Over the past few decades, compelling evidence from astrophysics has confirmed the presence of dark matter (DM) in the Universe [1,2]. This evidence is drawn from multiple observational phenomena, such as the rotation curves of galaxies, fluctuations in the cosmic microwave background, and the effects of gravitational lensing [3–5]. According to contemporary cosmological data [6,7], DM makes up roughly 85% of all matter in the Universe, a constituent that remains unaccounted for by the Standard Model (SM).

The inelastic DM (iDM) scenario was introduced [8–10] to account for unusual signals detected by the DAMA collaboration [11]. Since then, it has developed into a compelling theoretical framework for sub-GeV thermal DM that couples through SM photon [12–16], hidden vector [17–26], and scalar [27–31] mediators.

Current and projected experimental constraints on iDM particles motivate several distinct search strategies across different facilities: (i) e^+e^- collider probes at LEP [32,33] and BABAR [23]; (ii) past electron beam dump experiment E137 [20,34]; (iii) proton beam dump experiments,

including the past CHARM [35–37] and NuCal [38,39] facilities, as well as the proposed SHIP [40] experiment; (iv) far-forward detectors at the LHC, exemplified by FASER [13,14,41]; (v) searches at high intensity frontier with the proposed MATHUSLA [13,42,43], FLArE [13,44], SND@LHC [45], CODEX-b [46,47], and FORMOSA [48] experimental facilities; and (vi) the Large Hadron collider probes of iDM at ATLAS [23,49], CMS [50,51], and LHCb [52,53] are presented in Ref. [47].

In this paper, we study the missing energy signature of iDM at the electron fixed-target experiment NA64e [22,28,54] that arises in the scenarios incorporating two Dirac DM fermions, with the lighter state denoted as χ_0 , and the heavier one as χ_1 . Their coupling to the SM photon field is mediated by a magnetic dipole moment (MDM) operator of dimension five. Specifically, the interactions are encoded in the following effective Lagrangian [13,14,55]

$$\mathcal{L} \supset \frac{1}{\Lambda_M} \bar{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu} + \text{H.c.}, \quad (1)$$

where Λ_M is the typical energy scale that governs the strength of the new physics nonrenormalizable coupling, $F_{\mu\nu}$ is the electromagnetic strength tensor, and $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$.

High-energy electrons scattering off nuclear targets offer a method for probing iDM, as depicted in Fig. 1. Namely, this search looks for missing energy in the reaction of electron scattering [56], which arises when: (i) an off-shell Standard Model photon, γ^* , produces a pair of hidden

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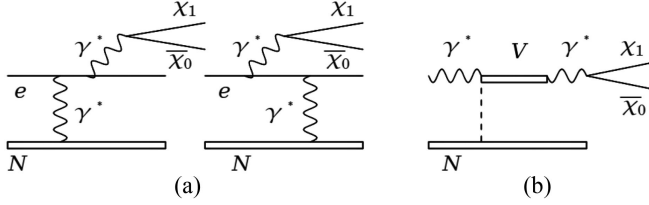


FIG. 1. Feynman diagrams illustrating the production iDM pairs in electron-nucleus scattering for two channels: (a) bremsstrahlunglike emission $eN \rightarrow eN\gamma^*(\rightarrow \chi_1\bar{\chi}_0)$; (b) reaction of vector meson photoproduction $\gamma^*N \rightarrow NV$ followed by its radiative decay $V \rightarrow \gamma^* \rightarrow \chi_1\bar{\chi}_0$ [13,14,57].

fermions, (ii) vector meson, $V = (\rho, \omega, \phi, J/\psi)$, photoproduction followed by its decay [57] into iDM particles,

$$e^-N \rightarrow e^-N\bar{\chi}_0\chi_1. \quad (2)$$

A crucial feature of the iDM model is the mass hierarchy within the dark sector. Specifically, the masses of the two fermions are not degenerate but exhibit a positive splitting, quantified by the parameter

$$\Delta = (m_{\chi_1} - m_{\chi_0})/m_{\chi_0} \gtrsim 0. \quad (3)$$

The presence of both the MDM operator (1) and the mass splitting (3) renders the χ_1 state unstable. This allows χ_1 to undergo a two-body decay, $\chi_1 \rightarrow \chi_0\gamma$, as illustrated in Fig. 2, producing, in principle, the single-photon semi-visible signature in NA64e. However, since for the iDM parameter space considered in this work the energy of the decay photon is $E_\gamma \ll 50$ GeV, which is a typical missing-energy threshold in the experiment, in the following we neglect the value of E_γ and assume that all the energy of the decay $\bar{\chi}_0\chi_1$ pair from the reaction of Eq. (2) is carried away from the detector, thus producing the missing-energy signature in the experiment. The consideration of the possibility to combine both the single-photon and missing-energy signatures that could enhance the sensitivity of the search is outside the scope of this work and will be considered elsewhere.

Our further analysis demonstrates the NA64e's capability to explore the unconstrained area of the iDM parameter space by using the missing-energy approach. Note, that the NA64e ultimate number of the expected electrons on target

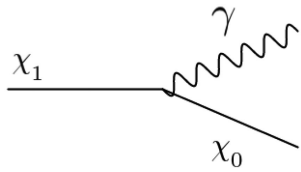


FIG. 2. Feynman diagram describing two-body radiative decay of the excited iDM state, χ_1 , into SM photon, γ , and lightest mode χ_0 .

(EOT) is assumed to be of the order of $EOT \simeq 10^{13}$. Achieving the desired sensitivity, will require suppressing the background level in NA64e down to $\lesssim \mathcal{O}(10^{-13})$ per incident electron, which seems quite possible [58]. Within this analysis, we examine exclusively the MDM interactions, given that the electric dipole moment operator [59–61] yields a similar result. Furthermore, we do not consider the anapole moment and charge radius terms [62–65], as their parameter space is severely constrained [13,14].

We emphasize that the effective operator (1) may emerge from a diverse range of ultraviolet (UV) completions. One possibility is that it originates from loop-mediated processes involving heavy states (an extra Dirac fermion ψ and a charged scalar doublet ϕ) with masses M on the order of a TeV or higher, which interact via the Yukawa coupling $\mathcal{L} \supset \lambda \bar{\psi} \chi \phi$ and carry Standard Model quantum numbers [66,67]. Above the electroweak symmetry breaking scale, these operators would likely be replaced by analogous expressions involving the $U(1)_Y$ and/or $SU(2)_L$ gauge fields present in the unbroken phase of the SM, rather than the photon [23]. The one-loop effective dipole DM coupling would scale as $1/\Lambda_M \propto \lambda^2 g'/M$, where g' is the hypercharge coupling constant. In the present paper, however, following the authors of Refs. [13,14], we will focus on the minimal dipole DM scenario (1), implying that the UV-completed states are sufficiently heavy, $M \gtrsim 1$ TeV. Consequently, there is an unconstrained parameter space for iDM in the sub-GeV mass range $10 \text{ MeV} \lesssim m_{\chi_0} \lesssim 1 \text{ GeV}$ with $1/\Lambda_M \lesssim 10^{-3} \text{ GeV}^{-1}$. In addition, as pointed out in Refs. [23,55,59], the effective coupling (1) can originate from the elastic limit, wherein a Dirac fermion χ_i acquires an additional Majorana mass term, thereby generating a small mass splitting, $\Delta \ll 1$. In this framework, further UV completion scenarios have been proposed in the literature, e.g., Refs. [68–72]. We leave a detailed analysis of the UV completion phenomenology for future work.

This paper is organized as follows. In Sec. II we outline the benchmark NA64e experiment. In Sec. III we discuss the rate of iDM pair production at NA64e associated with bremsstrahlunglike emission and vector meson decay. In Sec. IV, we derive the expected reaches of the NA64e fixed target facility in the iDM parameter space. In Sec. V we provide a summary and conclusion.

II. THE NA64E EXPERIMENT

The NA64e experiment makes use of a $E_e \simeq 100$ GeV electron beam delivered by the H4 beamline of the CERN SPS. This beam has the maximum intensity close to 10^7 electrons per spill of 4.8, s, and approximately 4000 such spills are considered usable on a daily basis.

If the iDM particles exist, they could be produced in the reaction of Eq. (2). In this process, the electron beam with the energy $E_e = 100$ GeV interacts with heavy nuclei of an active target, which is a lead-scintillator electromagnetic

calorimeter (ECAL). Following the interaction, the χ_1 state undergoes a rapid decay into $\bar{\chi}_0$ and a photon, $\chi_1 \rightarrow \chi_0 \gamma$. A considerable fraction of the initial beam energy E_{miss} , typically $E_{\text{miss}} \gtrsim 50$ GeV, is carried away from the detector by the $\chi_1 \bar{\chi}_0$ pair, leaving no activity in a hermetic hadronic calorimeter located downstream of the ECAL target. The residual energy, defined as $E_e^{\text{rec}} = E_e - E_{\text{miss}}$, is measured as a deposit in the ECAL from the recoil electron in the reaction (2). As a result, the presence of iDM particles would be identified through an excess of events characterized only by a single electromagnetic shower in the ECAL with the energy E_e^{rec} , exceeding the expected background levels (see, e.g., Ref. [73]).

There are several background sources in the NA64e experiment, which for the number of accumulated EOT $\simeq 10^{12}$ are rejected in total down to $b < 1$ events, for more details see, e.g., Ref. [74]. For the exposure with EOT $\simeq 10^{13}$, we assume that after the corresponding detector upgrade, the expected number of background events will be $b < 1$ event [58].

III. SIGNAL RATE

In this section, we discuss the production and missing energy signature of iDM associated with the reaction (2), which is similar to the ones previously used by NA64e in their searches for dark photons at the CERN SPS [58,74–79]. Specifically, in our analysis we focus on the iDM production through two primary production mechanisms (see, e.g., Fig. 1): (i) the reaction $e^- N \rightarrow e^- N \gamma^* (\rightarrow \chi_1 \bar{\chi}_0)$ that yields iDM pairs via an off-shell photon, γ^* , analogous to bremsstrahlung emission [80–82]; (ii) the exclusive photoproduction of a high-energy vector meson $V = (\rho, \omega, \phi, J/\psi)$ on a target nucleus N , via the reaction $\gamma^* N \rightarrow NV (\rightarrow \chi_1 \bar{\chi}_0)$. The initial photon γ^* in the reaction originates from standard bremsstrahlung process, $e^- N \rightarrow e^- N \gamma^*$ (for detail see, e.g., Ref. [83,84] and references therein).

As we discussed above, two-body decay, $\chi_1 \rightarrow \chi_0 \gamma$, is kinematically allowed for positive mass splitting $\Delta \gtrsim 0$. Its partial decay width is given by [13],

$$\Gamma_{\chi_1 \rightarrow \chi_0 \gamma} = \frac{\Delta^3 (\Delta + 2)^3 (m_{\chi_0})^3}{2\pi (\Delta + 1)^3 \Lambda_M^2}. \quad (4)$$

The decay length of χ_1 in the lab frame can be expressed for sufficiently small splitting $\Delta \ll 1$, as

$$d_{\chi_1} \simeq 1.5 \text{ m} \left(\frac{E_{\chi_1}}{10^2 \text{ GeV}} \right) \left(\frac{0.1 \text{ GeV}}{m_{\chi_0}} \right)^4 \left(\frac{0.05}{\Delta} \right)^3 \left(\frac{\Lambda_M}{10^3 \text{ GeV}} \right)^2, \quad (5)$$

where E_{χ_1} is the χ_1 energy. Note that Eq. (5) implies that two body decay $\chi_1 \rightarrow \chi_0 \gamma$ occurs within the length of the NA64e calorimetric system of $\lesssim 6$ m.

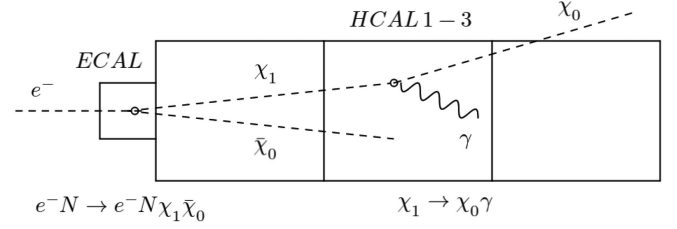


FIG. 3. Schematic view of a missing energy signature $V/\gamma^* \rightarrow \chi_1 \bar{\chi}_0 (\chi_1 \rightarrow \chi_0 \gamma)$ produced after a 100 GeV e^- scatters off in the active dump, $e^- N \rightarrow e^- N + E_{\text{miss}}$. The χ_1 particle decays within HCAL 1-3 into soft undetectable photon γ ($E_\gamma \lesssim 100$ MeV) and lightest sterile iDM state χ_0 . This sketch illustrates the NA64e setup to search for missing energy events [58,73–78].

As described in [14], the energy of a photon originating from $\chi_1 \rightarrow \chi_0 \gamma$ decay can be expressed in the lab frame as

$$E_\gamma = \frac{\Delta(2 + \Delta)}{2(1 + \Delta)} \left[\gamma_{\chi_1} + [(\gamma_{\chi_1})^2 - 1]^{1/2} \cos \theta_{\gamma\chi_1} \right] m_{\chi_0}, \quad (6)$$

where $\gamma_{\chi_1} \equiv E_{\chi_1}/m_{\chi_1}$ denotes the relativistic boost factor, and $\theta_{\gamma\chi_1}$ represents the angle, measured in the χ_1 rest frame, between the photon's direction and the χ_1 boost axis.

Furthermore, to ensure that the iDM final states remain invisible within the NA64e detector, i.e., the energy of the decay photon is small, we require the mass splitting also to be sufficiently small, $\Delta \ll 1$. Following Ref. [13], we adopt two benchmark splitting parameters: $\Delta = 10^{-3}$ and $\Delta = 5 \times 10^{-2}$.

Since the χ_1 particle effectively inherits its boost factor from the decaying meson that produced it, and given that the characteristic energy scale for the meson is $E_V \simeq \mathcal{O}(10^2)$ GeV, the resulting boost factor is estimated to be $\gamma_{\chi_1} \propto E_V/m_V \simeq \mathcal{O}(10)$. Consequently, the characteristic photon energy from these decays within our parameter space is $E_\gamma \simeq \gamma_{\chi_1} m_{\chi_0} \Delta \lesssim \mathcal{O}(10^{-2})$ GeV. A single photon with such an energy cannot be detected by the NA64e calorimeter, as the energy deposition threshold, E_{th} , is required to be sufficiently large, $E_\gamma \gtrsim E_{\text{th}} \simeq \mathcal{O}(1)$ GeV (see, e.g., Refs. [54,85] and references therein for detail).

This parametric suppression of the potentially visible decay $\chi_1 \rightarrow \gamma \chi_0$ ensures that both dark matter fermions escape the experiment undetected, resulting in a clean missing-energy signature (see Fig. 3).

A. Bremsstrahlunglike production: $\gamma^* \rightarrow \chi_1 \bar{\chi}_0$

The anticipated number of $2 \rightarrow 4$ missing-energy signature from the bremsstrahlunglike process [see Fig. 1(a)] can be estimated as,

$$N_{\gamma^* \rightarrow \chi_1 \bar{\chi}_0} \simeq \text{EOT} \cdot \frac{\rho N_A}{A} L_T \int_{E_{\text{min}}}^{E_{\text{max}}} dE_{\text{miss}} \frac{d\sigma_{2 \rightarrow 4}(E_e)}{dE_{\text{miss}}}, \quad (7)$$

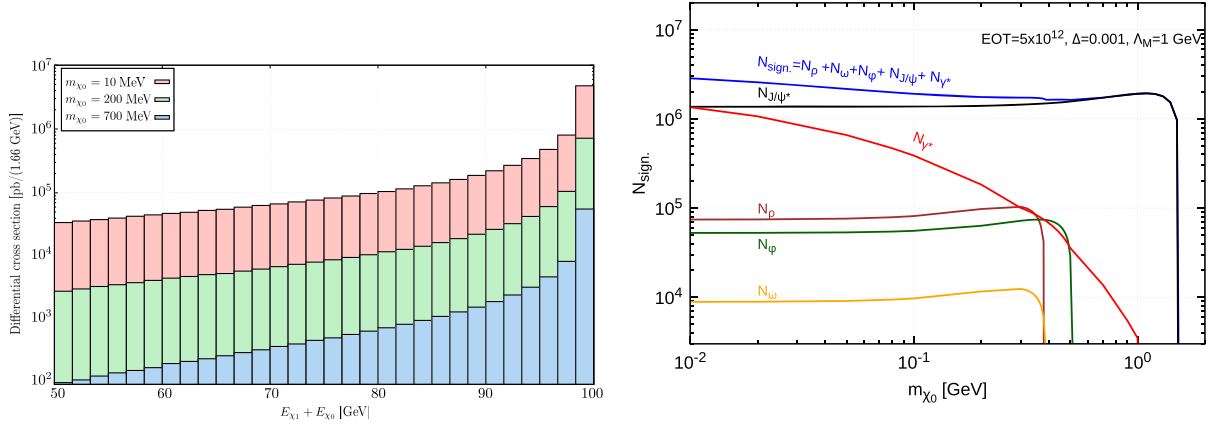


FIG. 4. Left panel: the differential cross sections of the process $e^-N \rightarrow e^-N\gamma^*(\rightarrow \chi_1\bar{\chi}_0)$ as function of the missing energy $E_{\text{miss}} = E_{\chi_1} + E_{\bar{\chi}_0}$ for the set of iDM masses in the range $10 \text{ MeV} \lesssim m_{\chi_0} \lesssim 700 \text{ MeV}$. The electron beam energy is $E_e \simeq 100 \text{ GeV}$, we also set $\Lambda_M = 1 \text{ GeV}$. Right panel: the plot shows the number of $\chi_1\bar{\chi}_0$ pairs produced versus χ_0 mass for NA64e (5×10^{12} EOT), with the splitting parameter chosen to be $\Delta = 10^{-3}$. The hidden particles are produced through the bremsstrahlunglike emission $\gamma^* \rightarrow \chi_1\bar{\chi}_0$ (red line), J-psi meson $J/\psi \rightarrow \chi_1\bar{\chi}_0$ (black line), rho meson $\rho \rightarrow \chi_1\bar{\chi}_0$ (brown line), omega meson $\omega \rightarrow \chi_1\bar{\chi}_0$ (orange line), and phi meson decay $\phi \rightarrow \chi_1\bar{\chi}_0$ (green line). The resulting number of $\chi_1\bar{\chi}_0$ pairs produced at the NA64e is shown by the blue line.

where ρ , A , and L_T denote the density, atomic mass, and effective length of the target, respectively. The symbol N_A represents Avogadro's number. The differential cross section $d\sigma_{2 \rightarrow 4}(E_e)/dE_{\text{miss}}$ describes the $2 \rightarrow 4$ bremsstrahlung-like process $e^-N \rightarrow e^-N\gamma^* \rightarrow eN\chi_1\bar{\chi}_0$, and $E_{\text{miss}} = E_{\chi_0} + E_{\bar{\chi}_0}$ is the total energy carried away by the invisible $\chi_1\bar{\chi}_0$ pairs. The integration limits E_{min} and E_{max} are set by the specific energy acceptance and selection criteria of the experimental setup. Specifically, candidate events are required to satisfy $E_e^{\text{rec}} \lesssim 0.5E_e$, corresponding to a lower integration limit of $E_{\text{min}} = 50 \text{ GeV}$ in Eq. (7).

Additionally, we assume that the electromagnetic shower in the ECAL is initiated within its radiation length of 0.56 cm . This defines the effective interaction length in Eq. (7) as $L_T \simeq X_0$, implying that the dominant production of hidden particles occurs within the first X_0 of the ECAL [60].

We compute the relevant $2 \rightarrow 4$ cross sections using the CalcHEP software package [86]. We have extended the SM implementation in CalcHEP by introducing two new massive particles: the excited iDM state χ_1 and the lightest χ_0 mode.

The left side of Fig. 4 shows how the differential cross sections change with the missing energy, E_{miss} , within the signal box region, where $0.5E_e \lesssim E_{\text{miss}} \lesssim E_e$. These plots are shown for various dark matter masses m_{χ_0} . A clear peak appears in the NA64e data near $E_{\text{miss}} \simeq E_e$, meaning the cross section rises sharply in that range. This points to a strong forward focus when $E_{\text{miss}} \gg m_{\chi_0}$, which implies that most of the beam energy goes into producing the inelastic dark matter pairs. The numerical simulations reveal that the shape of the differential cross section depends weakly on Δ , as long as we chose it sufficiently small, $\Delta \ll 1$. This also holds for the magnitude of the differential cross section.

B. Production via vector meson decays: $V \rightarrow \chi_1\bar{\chi}_0$

In this section, we rely on the comprehensive analysis of Ref. [83], in which the authors explicitly calculated the yield of vector meson exclusive photoproduction (involving both coherent and incoherent processes) based on HERA data fit [87,88] and the Glauber optical model [89]. Specifically, the anticipated number of vector mesons originating from the hard bremsstrahlung reaction $\gamma^*N \rightarrow NV$ at NA64e can be expressed as [83],

$$N_V = \text{EOT} \times f_{\text{brem}} \times P_V,$$

where f_{brem} denotes the fraction of beam electrons that emit a hard bremsstrahlung photon with sufficient energy to generate the meson, and P_V represents the probability for such a photon to undergo an exclusive photoproduction interaction on the target nucleus. Adopting the prescription of Ref. [83], the photoproduction probability can be approximated by

$$P_V \simeq \frac{9}{7} \frac{\sigma_0^V X_0 f_{\text{nuc}}^V}{m_p},$$

where X_0 is the radiation length of the target material, σ_0^V is the exclusive photoproduction cross section on a single nucleon, and f_{nuc}^V is an $\mathcal{O}(1)$ nuclear correction factor.

The expected signal yield from invisible vector meson decay into an iDM pair [see Fig. 1(b)] is expressed as

$$N_{V \rightarrow \chi_1\bar{\chi}_0} \simeq N_V \times \text{Br}_{V \rightarrow \chi_1\bar{\chi}_0}, \quad (8)$$

TABLE I. Parameters relevant for our analysis: vector meson mass m_V , number of mesons N_V produced for EOT $\simeq 5 \times 10^{12}$ at NA64e, and visible branching fraction to e^+e^- .

V	M_V (MeV)	N_V [83]	$\text{Br}_{V \rightarrow e^+e^-}$ [90]
ρ	775	1.2×10^8	4.7×10^{-5}
ω	782	9×10^6	7.3×10^{-5}
ϕ	1019	8×10^6	2.9×10^{-4}
J/ψ	3097	1.1×10^5	5.9×10^{-2}

where N_V denotes the total count of the given vector meson for NA64e, and $\text{Br}_{V \rightarrow \chi_1 \bar{\chi}_0}$ corresponds to its invisible branching fraction within the iDM framework [13],

$$\text{Br}_{V \rightarrow \chi_1 \bar{\chi}_0} \simeq \text{Br}_{V \rightarrow e^+e^-} \times \frac{(M_V^2 + 2m_{\chi_0}^2(2 + \Delta)^2)}{2\pi\alpha\Lambda_M^2 M_V^4} \times (M_V^2 - m_{\chi_0}^2 \Delta^2) \lambda(M_V^2, m_{\chi_0}^2, m_{\chi_0}^2(1 + \Delta)^2)^{\frac{1}{2}}, \quad (9)$$

where M_V is the mass of vector meson, $\text{Br}_{V \rightarrow e^+e^-}$ is the branching ratio corresponding to the $V \rightarrow e^+e^-$ decay, which we took from the Ref. [90]. We neglected the mass of the electron, m_e , in the denominator of Eq. (9), implying that $M_V \gg m_e$, we also exploit the following notation for the Kallen function

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc.$$

For the projected NA64e integrated statistics corresponding to EOT $\simeq 5 \times 10^{12}$, the expected yields of light vector mesons, N_V , are calculated by authors of Ref. [83]. We collect the specific numbers in Table I. These estimates [91] imply a characteristic fraction of hard-bremsstrahlung electrons of approximately $f_{\text{brem}} \simeq 0.5$.

The total amount of missing-energy signatures is then given by

$$N_{\text{sign}} \simeq N_{\gamma^* \rightarrow \chi_1 \bar{\chi}_0} + \sum_V N_{V \rightarrow \chi_1 \bar{\chi}_0}. \quad (10)$$

The right panel of Fig. 4 displays the total number of $\chi_1 \bar{\chi}_0$ pairs generated at the NA64e experiment as a function of m_{χ_0} .

For sufficiently light masses, specifically $m_{\chi_0} \lesssim 100$ MeV, the NA64e signal from exclusive J/ψ photo-production reaches a magnitude comparable to that of $\gamma^* \rightarrow \chi_1 \bar{\chi}_0$. The overall missing-energy signature count exhibits only a mild dependence on the mass m_{χ_0} , resulting in a relatively flat behavior across the sub-GeV region.

Although ϕ mesons are produced at lower rates than ω mesons, their invisible decays can nonetheless provide a larger signal contribution due to their enhanced branching

fraction, as illustrated in Fig. 4. Nevertheless, over the entire mass range of interest $10 \text{ MeV} \lesssim m_{\chi_0} \lesssim 1.5 \text{ GeV}$, the production of ρ , ω , and ϕ vector mesons at NA64e remains subleading with respect to the J/ψ meson.

It is worth noticing from the right panel of Fig. 4 that there is a bump in the NA64e signal observed below the threshold $m_{\chi_0} \lesssim M_{J/\psi}/2 \simeq 1.5 \text{ GeV}$ due to the contribution from the J/ψ vector meson decay to the total yield [14].

The dominant contribution to the signal yield of the sufficiently heavy vector meson J/ψ can be understood from the proportionality of the branching ratio to its mass squared, given that the number of such mesons produced is sufficient in the reaction $e^-N \rightarrow e^-NV(\rightarrow \chi_1 \bar{\chi}_0)$ (see, e.g., Ref. [83] and references therein). To be more specific, Eqs. (8) and (9) for approach $M_V \gg m_{\chi_0}$ and $\Delta \ll 1$ imply that the typical number of missing energy events associated with the vector meson parametrically scales as

$$N_{V \rightarrow \chi_1 \bar{\chi}_0} \propto N_V \times \text{Br}_{V \rightarrow e^+e^-} \times M_V^2 / \Lambda_M^2. \quad (11)$$

Furthermore, despite the relatively small number of J/ψ mesons, $N_{J/\psi} \simeq 10^5$, compared to other mesons, the J/ψ has a sufficiently large visible branching fraction, $\text{Br}_{V \rightarrow e^+e^-} \simeq 5.9 \times 10^{-2}$ and a sufficiently high mass, $M_{J/\psi} \simeq 3 \text{ GeV}$, to maximize the yield of invisible decay signatures $J/\psi \rightarrow \chi_1 \bar{\chi}_0$ at the NA64e experiment (11), as can be seen from Table I. Consequently, J/ψ provides better sensitivity than lighter mesons in the mass range below the threshold $m_{\chi_0} \lesssim M_{J/\psi}/2 \simeq 1.5 \text{ GeV}$.

Remarkably, an analogous statement holds for the heavy vector mesons produced in proton beam dump facilities, $pp \rightarrow XV(\rightarrow \chi_1 \bar{\chi}_0)$ [13,14,61].

IV. EXPECTED SENSITIVITIES

In Fig. 5 we show by solid lines the expected reaches of NA64e solid lines. Specifically, by using Eq. (10) to calculate the expected number of $\chi_1 \bar{\chi}_0$ produced events, we derive projected exclusion limits on the portal coupling $1/\Lambda_M$ within the minimal inelastic magnetic dipole DM framework. Assuming a background-free search, $b \simeq 0$, and a null observation, $n_{\text{obs}} \simeq 0$, we set a 90% confidence level (CL) exclusion criterion corresponding to a signal yield of $N_{\text{sign}} \gtrsim 2.3$ events for EOT $\simeq 5 \times 10^{12}$.

To perform additional conservative projection, in Fig. 5 we also show the expected reaches of NA64e implying the anticipated statistics of EOT $\simeq 10^{13}$ for both a background-free, $b = 0$, and non-negligible number of regarding events, $b \simeq 1$ (see, e.g., Ref. [81,92] and references therein for details).

In Fig. 5 we show by a solid red line the excluded limits of NA64e for the current accumulated statistics [76] of EOT $\simeq 10^{12}$. To be more specific, the current bounds of NA64e reach the couplings at the level

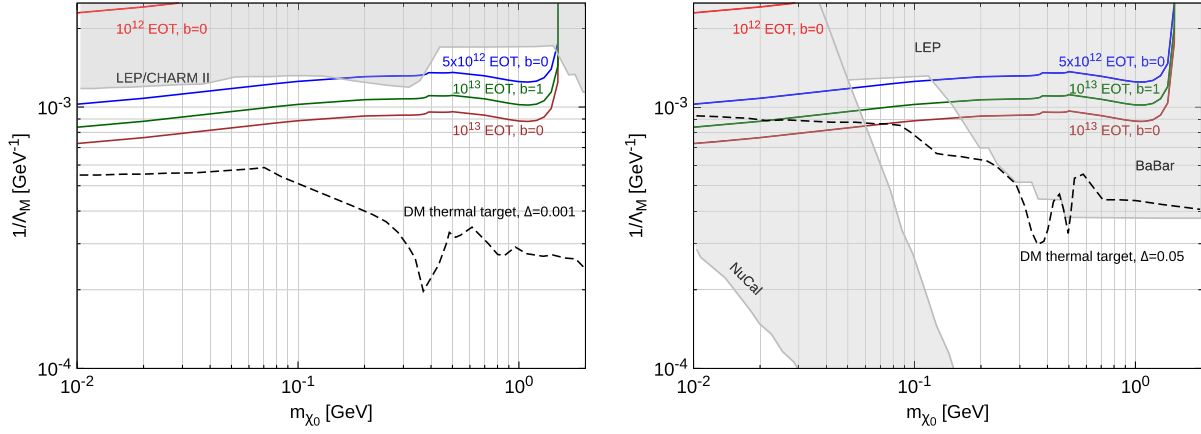


FIG. 5. Left panel: the expected limits at 90%CL on $1/\Lambda_M$ coupling for the NA64e fixed-target experiments as a function of the lightest iDM mass m_{χ_0} , implying mass splitting $\Delta = 10^{-3}$. Current limits of NA64e [74] are shown by the red solid line and imply the typical statistics of $\text{EOT} \simeq 10^{12}$, these bounds have been ruled out by LEP [32,33] and CHARM II [35,37] experiments (shaded gray region). The blue solid line is the projected sensitivity for the NA64e experiment for $\text{EOT} \simeq 5 \times 10^{12}$ and the background-free case, $b = 0$. The expected reaches of the NA64e ($\text{EOT} \simeq 10^{13}$) for the background-free, $b = 0$, and finite background case, $b = 1$, are shown by brown and green solid lines, respectively. The iDM thermal target curve is shown by the black dashed line, it was adapted from Ref. [13]. Right panel: the same as for the left panel, but for the benchmark mass splitting chosen to be $\Delta = 0.05$. The grey shaded region is ruled out from the BABAR [23], NuCal [38,39], and LEP [32,33] data, adapted from [13].

of $1/\Lambda_M \gtrsim 2 \times 10^{-3} \text{ GeV}^{-1}$ for the masses of interest, $m_{\chi_0} \lesssim 1.5 \text{ GeV}$, however these bounds have been already ruled out by other experiments for both benchmark splittings, $\Delta = 10^{-3}$ and $\Delta = 5 \times 10^{-2}$. We note that the projected limits of NA64e for $\text{EOT} \simeq 5 \times 10^{12}$ can rule out the typical couplings at the level of $1/\Lambda_M \gtrsim (1.0\text{--}1.5) \times 10^{-3} \text{ GeV}^{-1}$ for sub-GeV dark iDM masses.

The thermal freeze-out production mechanism involving magnetic dipole iDM has been analyzed in detail in Ref. [13]. In Fig. 5, we show the typical thermal target curves for two specific benchmark splittings, $\Delta = 10^{-3}$ and $\Delta = 5 \times 10^{-2}$, adapted from Ref. [13] (dashed black lines in Fig. 5). These lines imply that increasing the mass splitting value Δ shifts the relic curves upward relative to the constraints. As a result, a splitting of $\Delta = 10^{-3}$ spans sufficiently small couplings in the range $2 \times 10^{-4} \text{ GeV}^{-1} \lesssim 1/\Lambda_M \lesssim 6 \times 10^{-4} \text{ GeV}^{-1}$, while the larger $\Delta = 5 \times 10^{-2}$ implies a more mitigated range for the coupling constant $10^{-3} \text{ GeV}^{-1} \lesssim 1/\Lambda_M \lesssim 3 \times 10^{-3} \text{ GeV}^{-1}$. This means that NA64e is able to reach only a small fraction of the iDM thermal target curve, $1/\Lambda_M \simeq 9 \times 10^{-4} \text{ GeV}^{-1}$, for $\Delta = 5 \times 10^{-2}$ and masses around $m_{\chi_0} \lesssim 100 \text{ MeV}$, implying a sufficiently high number of electrons accumulated on target $\text{EOT} \lesssim 10^{13}$ and a background-free case.

In concluding this section, we note that the choice of the two sufficiently small benchmark values, $\Delta = 10^{-3}$ and $\Delta = 5 \times 10^{-2}$, is motivated as follows. The typical mass splitting range $10^{-3} \lesssim \Delta \lesssim 5 \times 10^{-2}$ is viable [13,14] in light of the dark matter thermal target parameter space [6,7]

associated with the observed relic abundance $\Omega h^2 \simeq 0.12$. Thermal target curves with sufficiently large mass splittings, $\Delta \gtrsim 0.05$, have already been ruled out by other experiments [13,14], as for such values the thermal target curve shifts toward the constrained region. By contrast, the unconstrained thermal target curves with relatively small mass splittings, $\Delta \ll 10^{-3}$, almost coincide with the elastic DM case [13,14], for which $\Delta = 0$. Thus, the thermal target curves with viable mass splitting in the range, $10^{-3} \lesssim \Delta \lesssim 5 \times 10^{-2}$, are motivated by the existed accelerator based experimental constraints.

V. SUMMARY AND CONCLUSION

In the present paper, we have studied the missing-energy signatures for the iDM production in the electron fixed target experiment NA64e at the CERN SPS. In particular, we calculated the production rate of the magnetic-dipole iDM pairs in the reaction $e^- N \rightarrow e^- N \chi_1 \bar{\chi}_0$. Based on this study, we have determined the expected sensitivity of NA64e to probe such particles with the anticipated statistics of $\lesssim 10^{13}$ electrons accumulated on target.

We show that accounting for heavy vector mesons decays, $\gamma^* N \rightarrow NV (\rightarrow \chi_1 \bar{\chi}_0)$ along with bremsstrahlunglike emission of iDM pairs, $e^- N \rightarrow e^- N \gamma^* (\rightarrow \chi_1 \bar{\chi}_0)$, will allow NA64e to probe still unexplored regions of iDM parameter space with sufficiently small splittings, $\Delta = 5 \times 10^{-2}$, and relatively light masses $m_{\chi_0} \lesssim 100 \text{ MeV}$. To achieve the required sensitivity an upgrade of the NA64e setup is currently in progress [58,75,93].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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