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Searching for Light Dark Matter and Dark Sectors with the NA64 experiment at the CERN SPS

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Abstract

Since its approval in 2016, NA64 has pioneered Light Dark Matter (LDM) searches with electron [1], positron [2], muon [3], and hadron [4] beams. The experiment has successfully met its primary objectives, as outlined in the EPPS input (2018), and even exceed them producing results that demonstrate its ability to operate in a near-background-free environment. The Physics Beyond Collider (PBC) initiative at CERN recognizes NA64's contributions as complementary and worthy of continued exploration. Its key advantage over beam-dump approaches is that the signal rate scales as $(\text{coupling})^2$ rather than $(\text{coupling})^4$, reducing the required beam particles for the same sensitivity.

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To fully exploit the NA64 physics potential, an upgrade during LS3 will enable NA64 to run in background-free mode at higher SPS beam rates. Planned upgrades include (a) improved detector hermeticity with a new veto hadron calorimeter, (b) enhanced particle identification with a synchrotron radiation detector, and (c) increased beam rates via upgraded electronics.

With the recently strengthened NA64 collaboration, stable operations and timely data analysis are planned for LHC Run 4. The expected $\sim 10^{13}$ electrons, $\sim 10^{11}$ positrons (40 and 60 GeV), and $\sim 2\times10^{13}$ muons on target will allow NA64 to explore new light dark matter regions, with the potential for discovery or conclusive exclusion of many well-motivated LDM models.

Keywords: LDM, dark photon

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1. Introduction

Despite intensive searches at the LHC and in non-accelerator experiments, Dark Matter (DM) remains a mystery that challenges our understanding of the Universe (see, e.g., [5] for a recent review). One of the most popular and extensively searched-for thermally produced DM candidates falls under the category of Weakly Interacting Massive Particles (WIMPs), a term that encompasses the lightest supersymmetric particles, Kaluza–Klein states from extra-dimensional models and others. The negative results from the extensive WIMP detection program are pushing further investigations toward the high-energy and high-sensitivity frontiers (see, e.g., [6] and references therein).

In recent years, a variety of alternative DM candidates have been proposed to address this fundamental question. A broad class of well-motivated models introduces the concept of "Dark" (or hidden) Sectors (DS), providing a natural framework to explain the origin and properties of DM. In these models, DM is part of a hidden sector composed of particles that are singlets under the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group of the Standard Model (SM), interacting with ordinary matter through gravity and potentially other feeble forces.

From an experimental perspective, the sensitivity of searches for these new singlet states depends on the coupling strength and mass scale of the dark particles. To probe the parameter space of the most motivated DS theories, it is essential to employ a combination of search techniques optimized for different mass ranges and interaction strengths.

One of the most intriguing scenarios postulates the existence of a new portal interaction between the DS and visible matter, mediated by a new vector boson A', the so-called *dark photon*. The A' could be light, with a mass $m_{A'} \lesssim 1$ GeV, associated with a spontaneously broken $U(1)_D$ gauge symmetry. The Standard Model and the A' may communicate via a kinetic mixing term involving the ordinary photon. This interaction is described by the additional term $-\frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu}$ in the massive photon Lagrangian, parameterized by a small mixing strength $\epsilon \ll 1$. Dark photons with masses at the sub-GeV scale can arise in various physics scenarios. If the additional secluded $U(1)_D$ symmetry is embedded in a Grand Unified Theory (GUT), the mixing can be generated at the one- or two-loop level, naturally yielding values of $\epsilon \simeq 10^{-3} - 10^{-1}$ (one loop) or $\epsilon \simeq 10^{-5} - 10^{-3}$ (two loops) [7–9]. The concept of sterile photons was first introduced by Okun in his paraphoton model [9] (see also [8]).

One of the strongest motivations for the existence of light Dark Sectors is that they offer a viable framework to explain DM as a thermal freeze-out relic in a broader and lower mass range compared to WIMPs [10]. In Light Dark Matter (LDM) models, the dark state can account for the observed DM relic density [11, 12] through the so-called "WIMPless miracle."

This possibility has sparked a worldwide theoretical and experimental effort to search for dark forces and other portals connecting the visible and hidden sectors. As a result, the focus has shifted from high-energy colliders to the high-intensity frontier (see, e.g., [13–16] for a review). DS could also provide a solution to other open questions of the SM such as the origin of the neutrino mass and the strong CP problem.

2. Brief history of NA64

The NA64 experiment at CERN's SPS was primarily designed to search for sub-GeV dark-sector particles that interact with the SM ones via light mediators, potentially explaining the origin of dark matter. These theoretically well-motivated and cosmologically viable scenarios are challenging to probe with traditional DM detection methods. The experiment, later called NA64e, effectively combining active target and missing-energy techniques and using 50–100 GeV electron and positron beams, achieved the best sensitivity to dark photon models with hypercharge kinetic mixing. World-leading constraints on Light DM (LDM) obtained from 2016–2023 runs have been set [1], probing a part of the key parameter space that explains the observed dark matter relic abundance.

At the same time, other obtained results demonstrate that NA64 exceeded its primary goals and developed a broader dark sector program created from the initially proposed NA64e experiment without compromising the searches for LDM. This research program provides important inputs for many new physics scenarios, including the ^{8}Be anomaly [17], axion-like particles (ALPs) [18, 19], electron $g-2$ [20], inelastic dark matter [21, 22], $B-L$ [23], $L_\mu - L_\tau, Z'$ models [24], and Lepton Flavour Violation (LFV) [25–28]. The experiment also complements underground direct detection, neutrino, beam dump, and high-energy collider searches, providing crucial physics input and motivation for the current and future experimental research program at CERN.

In 2018, NA64 proposed extending its search for higher-mass LDM using the SPS M2 160 GeV muon beam [29]. Investigating the simplest Z' extension governed by $L_\mu - L_\tau$ currents was a crucial step, given its possibility to address both the muon $g-2$ anomaly and the DM relic density. Pilot experimental runs with muons in 2022 effectively dismissed most of the $g-2$ explanation and imposed the first limitations on LDM connected to the second generation of leptons [3]. In 2022, the first pilot measurement was performed by NA64, using a 100 GeV positron beam to maximally exploit the resonant annihilation channel to search for LDM. The results demonstrate the validity of this approach, identifying the corresponding critical items and determining an appropriate strategy to mitigate them, in view of the planned future full-scale e^+ program [30]. A short 2023 test run with a pion beam [4] set stringent limits on invisible η and η' decays, demonstrating that NA64's sensitivity to leptophobic dark matter could be significantly enhanced in future runs. This opens up an additional line of research at NA64 for exploring a new class of dark sector models with hadron beams.

3. NA64-e^-: Status and prospects

The baseline configuration of the experiment (NA64e) makes use of a 100 GeV electron beam, optimized and supplied by the H4 beamline located in the North Area. Designed for high-intensity operation, the beamline can transport roughly $\simeq 10^7$electrons per 4.8 s SPS spill within the 50–150 GeV$/c$ momentum range. Beam composition studies have confirmed minimal hadronic pollution, constraining the π/e^- ratio $\lesssim 0.5\%$ [31].

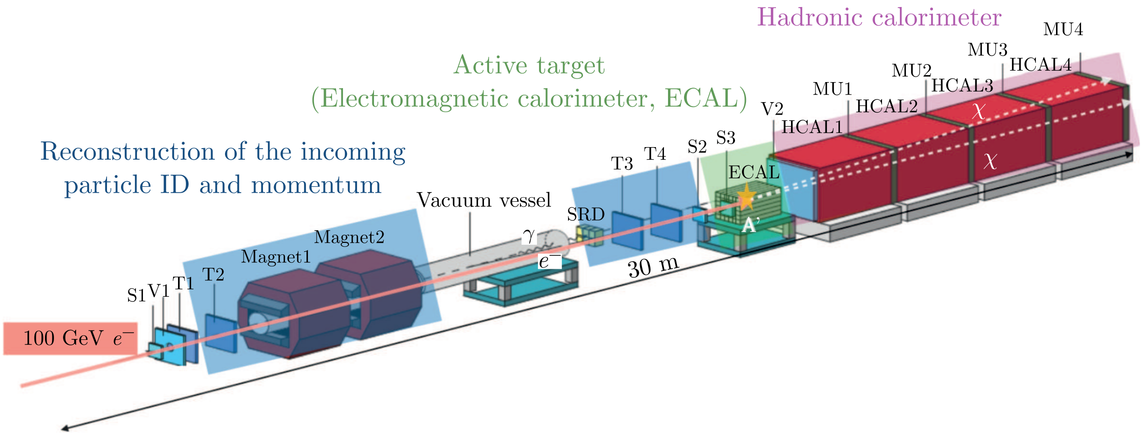

Figure 1. NA64 schematic configuration and detection principle for dark photons via the missing energy signature in the ECAL serving as an active target.

Searching for invisible decays of massive A' is the goal of NA64, which utilizes a combination of missing energy measurements and the active beam dump technique. In the ECAL target, dark photons are produced via dark bremsstrahlung, specifically through the reaction $e^- Z \to e^- Z A'$, involving electron scattering off nuclei with charge Z [32, 33]. The signature arises when the A' promptly decays into invisible LDM pairs ($A' \to \chi\chi$) that escape detection, resulting in a missing energy signature. This defines the 'invisible' search strategy. NA64 aims to explore the thermal freeze-out relic region, specifically where $m_{A'}$ is in the sub-GeV range and $10^{-6} < \epsilon < 10^{-3}$. Success in missing energy experiments depends critically on precise beam monitoring and accurate calorimetric measurement of deposited energy.

Signal events manifest themselves as isolated electromagnetic showers in the ECAL, carrying energy E_{ECAL}, while exhibiting a significant energy deficit given by $E_{\mathrm{miss}} = E_{A'} = E_{\mathrm{initial}} - E_{\mathrm{ECAL}}$. An excess of these events relative to background expectations would indicate A' production (a schematic setup and its working principle are provided in Figure 1).

With the 2016–2022 combined statistics, NA64 sets the most stringent upper limits in the kinetic mixing (ϵ) and dark photon (A') mass plane for masses below 350 MeV. The collected data also allow constraining the values of scalar and Majorana DM with coupling $\alpha_D \leqslant 0.1$ and $m_{A'} > 3m_\chi$ in the mass range $0.001 \leqslant m_\chi \leqslant 0.1$ GeV as presented in Figure 2. The latest results with the 2016–2022 collected statistics were published in *Phys. Rev. Lett.* [31] and the paper was highlighted as an Editor's suggestion.

Beyond the dark Bremsstrahlung mechanism, the resonant production of A' via annihilation of beam electrons with positrons from the electromagnetic shower has also been taken into account. The resulting 90% C.L. exclusion bounds from the joint analysis are presented in Figure 2, where the characteristic peak in the limits originates from the resonant annihilation channel (see Section 4 for a detailed discussion). Incorporating this additional production mode enhances the experimental sensitivity at higher masses, a region where the bremsstrahlung signal rate is suppressed by the $1/m_{A'}^2$ scaling of its cross-section (see [35] for more information).

NA64 has also a great potential to probe scenarios beyond the dark photon hypothesis. The NA64 experiment has already shown sensitivity to light scalar and pseudoscalar ALPs generated through the Primakoff process [18], thereby constraining a portion of the parameter space previously unbounded between beam-dump experiments and LEP bounds (see Figure 3, top left). The experiment also excluded a significant portion of the parameter space relevant for the hypothesized X17 boson, which could explain the beryllium anomaly [17, 34] (see Figure 3, top center).

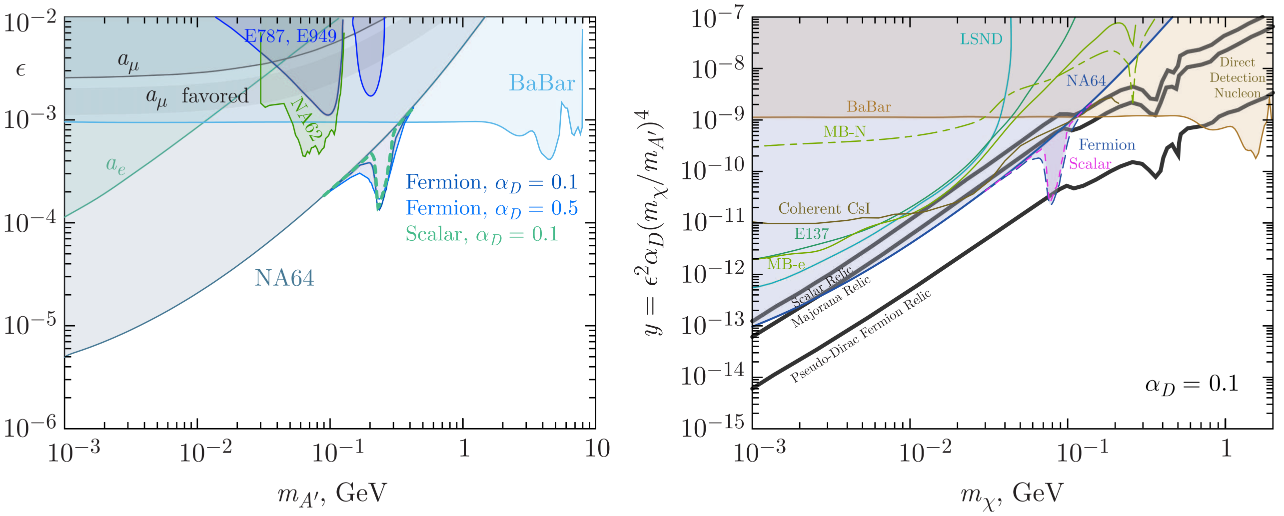

Figure 2. Left: present constraints of the NA64 experiment: 90% C.L. exclusion bounds on invisible A' decays, incorporating both dark bremsstrahlung and resonant A' production mechanisms. Right: searches for light dark matter [31].

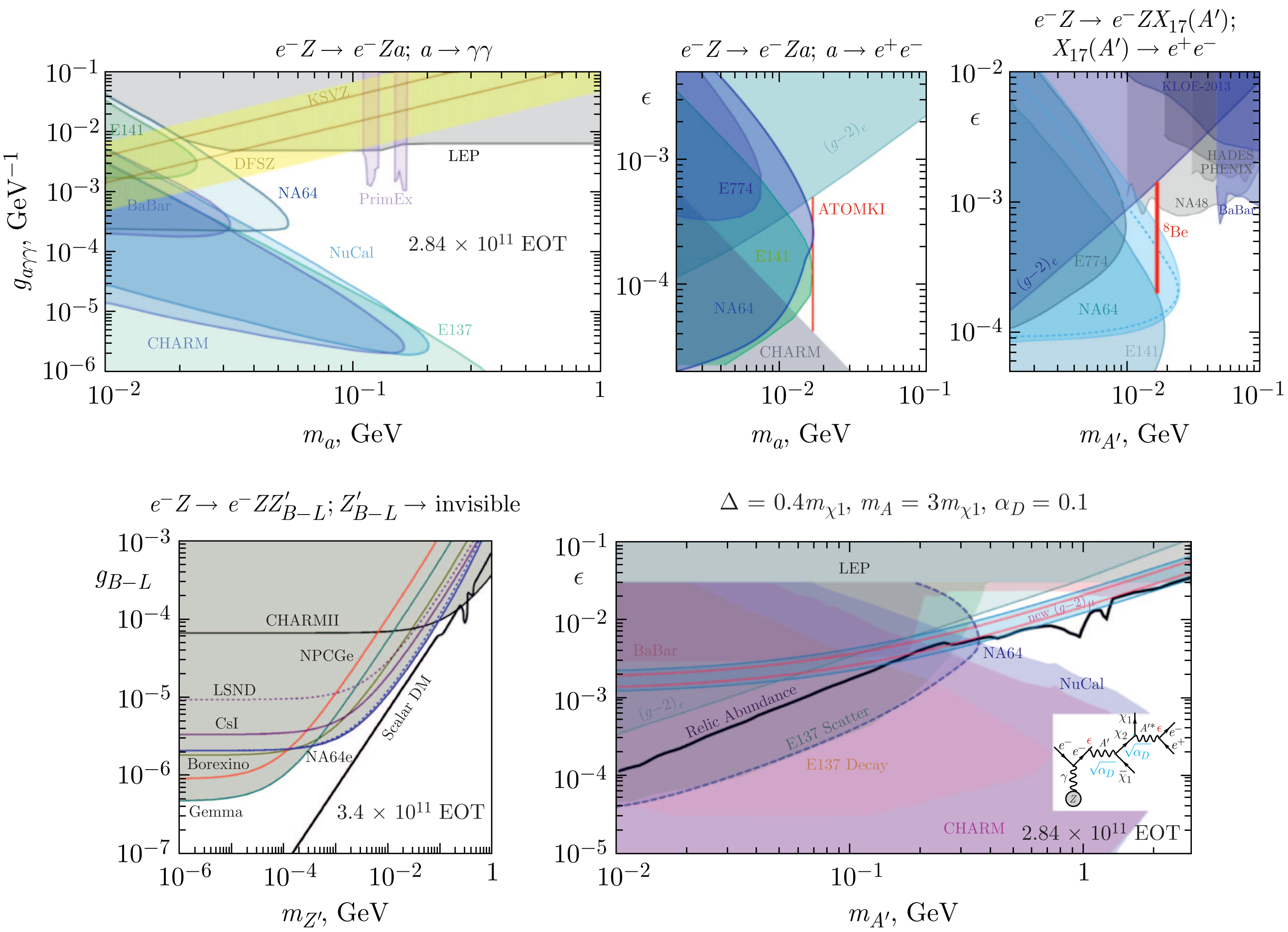

Figure 3. Latest NA64 results: 90% C.L. exclusion bounds on ALPs searches [18] (top left), pseudoscalar decaying to e^+e^- [34] (top center) and $A'(X)$ visible decays [17] (top right), and NA64 coverage for a new B–L Z' gauge boson [23] (bottom left) and semi-visible A' decays [21] (bottom right).

An investigation of a Z' gauge boson linked to (un)broken B–L symmetry covering the keV–GeV scale using 2021 data [23] set the most stringent limits for $0.3 \lesssim m_{Z'} \lesssim 100$ MeV, surpassing constraints from neutrino-electron scattering (see Figure 3, bottom left). NA64 also explored a Z' boson linked to the muon-tau lepton number difference, which could explain the muon $g-2$ anomaly and DM relic density [36]. With 2016–2022 data, the experiment probed the $(g-2)_\mu$-favored region for 1 keV $< m'_Z <$ 2 MeV [24, 37].

NA64 is also sensitive to inelastic Dark Matter (iDM) scenarios, where two DM species with a small mass splitting lead to unique topologies involving both missing and visible energy [22, 38, 39]. An initial recast analysis using 2016–2018 data [21] probed this signature (see Figure 3, bottom right) and was featured on the cover of *European Journal of Physics C* 81/10.

Additionally, NA64 enables searches for Lepton Flavour Violation (LFV) in processes like $e^-N \to \mu^- N Z'$ [40]. In 2023, a magnet spectrometer was added to identify final-state muons from electron interactions. The first feasibility study based on Monte Carlo simulations optimized the setup for LFV searches and was recently published [28].

A prototype veto hadron calorimeter (VHCAL), composed of Cu–Sc layers, was added to the downstream NA64 setup at the CERN SPS H4 beamline in 2023 to improve sensitivity. The VHCAL was designed to efficiently veto large-angle hadrons produced via upstream electroproduction or photon-nuclear interactions, thereby suppressing background contributions from secondary particles that exit the detector acceptance. Analysis of the collected 4.4×10^{11} electrons on target (EOT) demonstrates that this approach suppresses such background by more than an order of magnitude. This result represents a crucial step toward realising a full-scale, optimized VHCAL for background-free running in LHC Run 4, where 10^{13} EOT is projected.

4. NA64-e^+: Status and prospects

The use of a positron in a missing-energy experiment allows one to maximally exploit the resonant annihilation channel to search for LDM. In the reaction, a positron from the shower — either the primary or a secondary one — annihilates with an atomic electron, resulting in the production of an LDM pair; in the simpler model, this involves the exchange of an on-shell dark photon ($e^+e^- \to A' \to \chi\overline{\chi}$) [41]. Thanks to the resonant nature of the process, the signal yield is strongly enhanced in the allowed kinematic region, roughly corresponding to the interval $\sqrt{2m_e E^{\mathrm{thr}}_{\mathrm{miss}}} \lesssim m_{A'} \lesssim \sqrt{2m_e E_0}$, where E_0 is the beam energy and $E^{\mathrm{thr}}_{\mathrm{miss}}$ the missing energy threshold. The resonant reaction is also characterized by a unique signature of the signal, manifesting itself as a narrow peak in the missing energy distribution, whose position solely depends on the A' mass value.

A first pilot measurement was performed by NA64 in summer 2022, using a 100 GeV positron beam and accumulating a total statistics of $\simeq 10^{10}$ e^+OT [2], with average intensity of about 5×10^6 particles/spill. The main goal of the measurement was to demonstrate, for the first time, the validity of the positron-beam missing-energy technique to search for LDM, identifying the corresponding critical items and determining an appropriate strategy to mitigate them, in view of a future full-scale e^+ program. During this measurement, the H4 beamline optics was reversed to transport positively charged particles, with a corresponding beam purity of about 96% [31], slightly larger than the value corresponding to the negative-charge configuration. Due to this, the largest background source expected in the measurement, with an expected yield of about 0.06 events, was from the in-flight decay of misidentified π^+ and K^+ to a $e^+\nu_e$ pair, with the soft electron giving rise to a low-energy EM shower in the ECAL. After scrutinizing the data, no events were observed in the signal region. This allowed NA64 to set new exclusion limits that, relative to the collected statistics, prove the power of this experimental technique, as depicted in Figure 4, left panel.

Motivated by this result, in 2023 NA64 performed a second positron-beam measurement, accumulating a total statistics of 1.6×10^{10} e^+OT at 70 GeV beam energy. A decrease in beam energy made it possible to investigate another area of the light dark matter parameter space, accomplished by tuning where the resonant annihilation peak occurs. The main goal of this measurement was to probe the hermeticity of the NA64 detector at lower beam energy, in view of a high-statistics post-LS3 program with multiple beam energies down to 40 GeV. Resulting in an improvement of hermeticity of the setup, mostly because of the installation of the VHCAL detector prototype in front of the ECAL, the signal region was extended by setting $E_{\rm miss}^{\rm thr} = 28$ GeV. In this configuration, the dominant background source was indeed due to events in which the primary beam particle interacts with upstream detector elements — scintillator counters and tracking detectors — resulting in a soft positron hitting the calorimeter and one

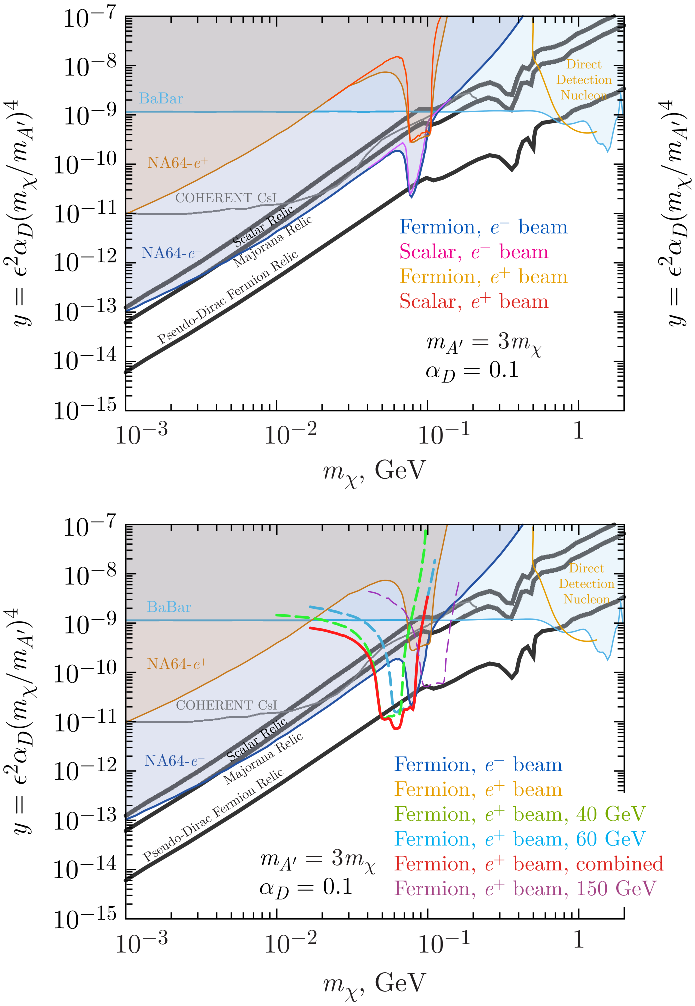

Figure 4. Top left: the exclusion bounds presented by the NA64 collaboration based on the 2022 missing-energy measurement with a 100 GeV positron beam, corresponding to an integrated statistics of 10^{10} positrons on target (e^+OT). Top right: same result from the 2023 positron-beam run at 70 GeV, with comparable statistics. Bottom: sensitivity of the post-LS3 NA64 positron-beam program, with two measurements at 40 and 60 GeV beam energy, each with total statistics of about 10^{11} e^+OT.

or more energetic secondary hadrons emitted at large angle, outside the detector acceptance. The corresponding yield, estimated from data by side-band projections, was about 0.09 events. No events were observed in the signal region, and new exclusion limits were set. A new region of the LDM parameter space was probed by NA64, benefiting from the considerable signal yield enhancement provided by the e^+e^- annihilation mechanism, particularly effective for primary positron beams. Vector-mediated light dark matter was excluded in the mass window $165 < m_{A'} < 220$ MeV, for ε values reaching 2.5×10^{-4} and $\alpha_D = 0.1$ (see Figure 4, right panel). To further enhance this result and probe other α_D values, in 2024 NA64 performed a third positron run at 70 GeV beam energy, accumulating a comparable statistics. To cope with the reduction of synchrotron-radiation emission at lower beam energy, the setup was improved by replacing the existing Synchrotron Radiation Detector with an optimized LYSO-based compact calorimeter. The data analysis is currently in progress, and results are expected by the end of 2026.

These successful efforts paved the way to the development of the NA64 post-LS3 program with positron beams, presented to the CERN SPSC in 2024 [30]. This program is supported by a dedicated ERC grant, POKER ("POsitron resonant annihilation into darK mattER"), aiming at a broad LDM search with positron beams, missing energy measurements [42]. Its goal is to perform a comprehensive measurement with positrons, with multiple runs at different energies, to "scan" the LDM parameter space for masses larger than ≈ 100 MeV, by varying the position of the resonant peak. Specifically, in the first phase (2028–2029) we plan to accumulate up to 10^{11} e^+OT at 60 and 40 GeV, allowing the LDM parameter space in the interval $135 \lesssim m_{A'} \lesssim 250$ MeV to be probed down to the coupling values expected from the Pseudo-Dirac Fermion Relic target model, assuming $\alpha_D = 0.1$ (see also Figure 4). In the second phase (2030–2032), instead, we aim at enhancing the accumulated statistics to probe larger α_D values, up to $\alpha_D = 0.5$, by running the experiment at larger beam intensity, with up to 3×10^7 positrons per SPS spill. This program presents significant challenges, mostly connected to the hermeticity of the setup at lower beam energy, as well as to the possibility of running the experiment at very high beam intensity. NA64 has already started a dedicated R&D program to tackle them, supported by the results already obtained from the 70 GeV measurement. Specifically, in order to enhance the background rejection capability of the detector at 40 GeV, a large VHCAL detector will be installed in front of the calorimeter. Another item of concern is the fact that, at 40 GeV, penetrating particles produced in the ECAL and interacting in the HCAL with a small energy deposition may be misidentified as zero-HCAL-energy events due to resolution effects of the latter. To mitigate this effect, we plan to improve the detector readout scheme, to increase the light collection efficiency.

5. NA64-h: Status and prospects

The NA64h is a fixed target experiment utilizing the pion, kaon, and proton beams at the CERN SPS and capable of detecting signal of BSM physics via hadron-nuclear scattering. It employs the missing energy technique and some of its specific signature [43]. The NA64h can explore a variety of sub-GeV DM models interacting with the SM via light mediators. Since the dominant production and detection modes for DM occur via hadronic nuclear scattering reactions, NA64h has a unique sensitivity to leptophobic (or hadrophilic) DM models with a mediator coupled predominantly to light quarks. These models could yield the correct thermal relic abundance and are difficult to test with NA64e and NA64μ experiments.

The NA64h plans to perform a comprehensive study of leptophobic models predicting

(i) a new $U'(1)$ gauge bosons or scalars coupled to LDM [44, 45];

(ii) invisible of semi-visible decays of neutral and vector mesons $\eta, \eta', \omega, \rho, \ldots$ [43, 46, 47], and, in particular, $K_{S,L} \to \textit{invisible}$ decays of neutral kaons, which have never been probed [43, 48, 49]. The latter is highly complementary to searches for $K^{+,0} \to \pi + \textit{invisible}$ decays;

(iii) K^0–K'^0 oscillations of neutral K^0 into its dark partner, e.g., in the Mirror Matter model [50, 51]. This search is complementary to experiments looking for $n - n'$ oscillations;

(iv) a class of dark sector models with a heavy neutral lepton [52] can also be tested.

In 2024, NA64h presented the first results from a proof-of-principle search for Dark Sector physics through invisible decays of pseudoscalar η and η' mesons at the CERN SPS [4]. The core technique relies on producing neutral mesons through charge-exchange reactions of 50 GeV π^- beams interacting with an active target. A signal event ($\eta, \eta' \to$ invisible$e$) would be characterized by a remarkable signature — the complete nondetection of the incoming beam energy within the detector. Analysis of 2.9×10^9 pions on target, accumulated during one day of running, yielded no evidence for such processes. Consequently, we derive a tight constraint $\mathrm{Br}(\eta' \to \text{invisible}) < 2.1 \times 10^{-4}$, surpassing the prior bound by approximately a factor of $\simeq 3$. We also obtain $\mathrm{Br}(\eta \to \text{invisible}) < 1.1 \times 10^{-4}$, compatible with current limits. These achievements highlight the significant potential of the technique and offer clear directions toward improved sensitivity for dark sector searches via invisible neutral meson decays in future searches [47]. We have already performed this program at the CERN PS T9 beamline. The first 2-week test beam studies at T9 were carried out in October 2025. An addendum to the SPSC with our future plans after LS3 is in preparation.

6. NA64-μ: Status and prospects

At the end of 2021, NA64 began its complementary program for exploring Dark Sectors at the M2 beamline of the CERN SPS. This unique beam can deliver high-energy 160 GeV muons with maximal intensities reaching up to 2×10^8 muons/spill, an order magnitude higher than that available for electrons and positrons at H4. This higher intensity potentially allows for acquiring significantly larger statistics, enhancing the sensitivity of searches for rare processes and feebly interacting particles. Production of hypothetical particles (X) may occur via a bremsstrahlung-like mechanism when 160 GeV muons interact with an active target, $\mu N \to \mu N X$, followed by decay into invisible final states ($X \to$ invisible). Under these circumstances, the observable signal would comprise an isolated muon scattered from the target, retaining approximately less than half its incoming energy, with no registered hits in sub-detectors placed after the interaction vertex [53]. To demonstrate the experiment proof of principle, we optimised a pilot run in 2022 to carry out such a search using a sub-GeV Z' charged under $U(1)_{L_\mu - L_\tau}$ as benchmark process.

For the collected 1.98×10^{10} MOT, the expected background within the signal box was estimated to be 0.07 ± 0.03. The main background source comes from the momentum misreconstruction in the magnet spectrometer downstream of the target. After unblinding, no events compatible with an invisible Z' charged under $U(1)_{L_\mu - L_\tau}$ decay in the signal region were found. These results enabled us to set the 90% C.L. upper limits on the coupling as a function

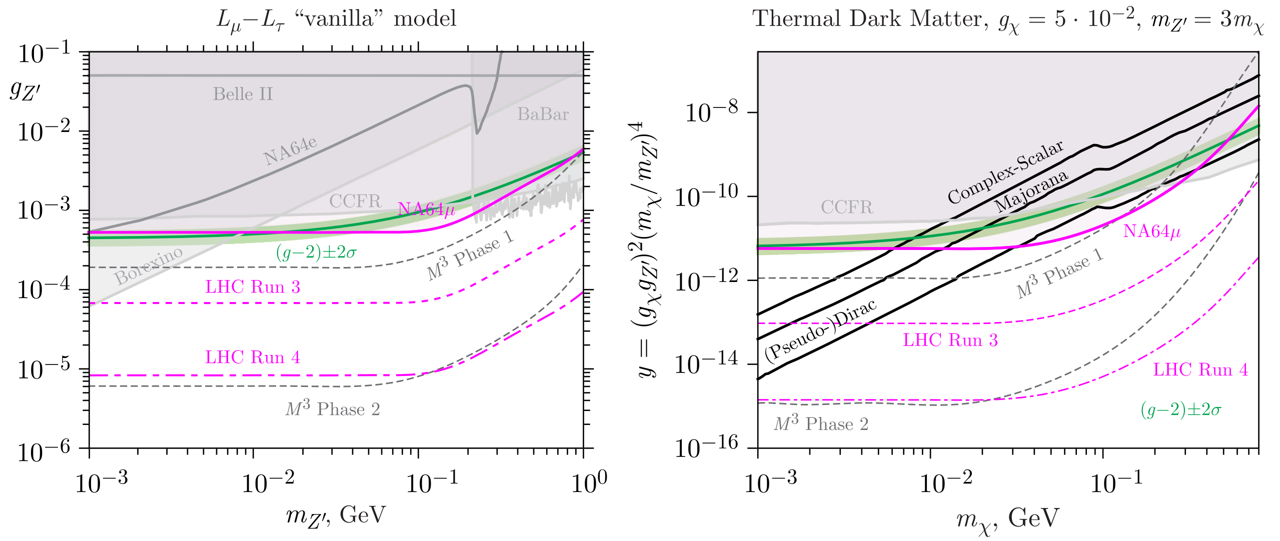

Figure 5. Left: NA64μ 90% C.L. exclusion limits on the coupling $g_{Z'}$ as a function of the Z' mass, $m_{Z'}$, for the vanilla $L_\mu - L_\tau$ model. Right: the 90% C.L. exclusion limits obtained by the NA64μ experiment in the $(m_\chi,\ y)$ parameters space for thermal Dark Matter charged under $U(1)_{L_\mu - L_\tau}$ with $m_{Z'} = 3m_\chi$ and the coupling $g_\chi = 5\times10^{-2}$ for 1.98×10^{10} MOT. The branching ratio to invisible final states is assumed to be $\mathrm{Br}(Z' \to \text{invisible}) \simeq 1$. Existing constraints from other experiments, and projections before and after LS3 are also shown.

of the Z' mass. In Figure 5 our constraints for two scenarios are illustrated. The left plot considers the minimal or *vanilla* model where Z' decays only to neutrinos. The green band shows the $\Delta a_\mu \pm 2\sigma$ region for the Z' contribution to the $(g-2)_\mu$ anomaly. In this case, NA64μ limits exclude masses $m_{Z'} \gtrsim 40$ MeV and coupling $g_{Z'} \gtrsim 6\times10^{-4}$. On the other hand, in extended scenarios, the Z' can decay to DM particles. NA64μ could probe a portion of the $(m_\chi,\ y)$ parameter space, with $y = (g_\chi g_{Z'})^2(m_\chi/m_{Z'})^4$. For $m_{Z'} = 3m_\chi$, chosen to be away from the resonant enhancement $m_{Z'} \simeq 2m_\chi$, and $g_\chi = 5\times10^{-2}$ (to probe the DM freeze-out prediction and the muon $g-2$ anomaly), our results constrain the dimensionless parameter y to $y \lesssim 6\times10^{-12}$ for $m_\chi \lesssim 40$ MeV.

NA64μ has also a unique sensitivity to other scenarios complementing the physics case accessible with electron and positron beams. As an example, in Figure 6, the 90% C.L. limits from NA64μ for scalar and vector mediators are illustrated [54]. The plot on the left, shows the results for Dark Photon searches using a muon beam. The current limit is not yet competitive compared to the other experiments but demonstrates our capability to probe masses above 100 MeV with higher statistics as shown with the projections for NA64μ before and after LS3. As shown in Figure 6, combined with our e^- and e^+ beam programs, NA64 can probe the full parameter space of benchmark LDM models.

In the right plot of Figure 6, the sensitivity in the case of a scalar mediator is depicted for the choice of parameters of coupling $g_\chi = 1$. Two different scenarios containing Dirac DM with the benchmark ratio $m_S/m_\chi = 3$ and the near-resonant regime $m_S/m_\chi = 2.1$ are considered. The corresponding thermal targets are extracted from [55]. Our limits cover part of the parameter space compatible with masses $m_S \leqslant 300$ MeV up to a coupling $g_S \sim 10^{-3}$ for the mass ratio $m_S/m_\chi = 3$. In the case of $m_S/m_\chi = 2.1$, the limits are only covering scalar masses up to $m_S \sim m_\mu$. More details on (i) the Monte Carlo (MC) approach used in simulating the signal events, (ii) systematics in the signal yields, and (iii) level of background extracted from data can be found in [54].

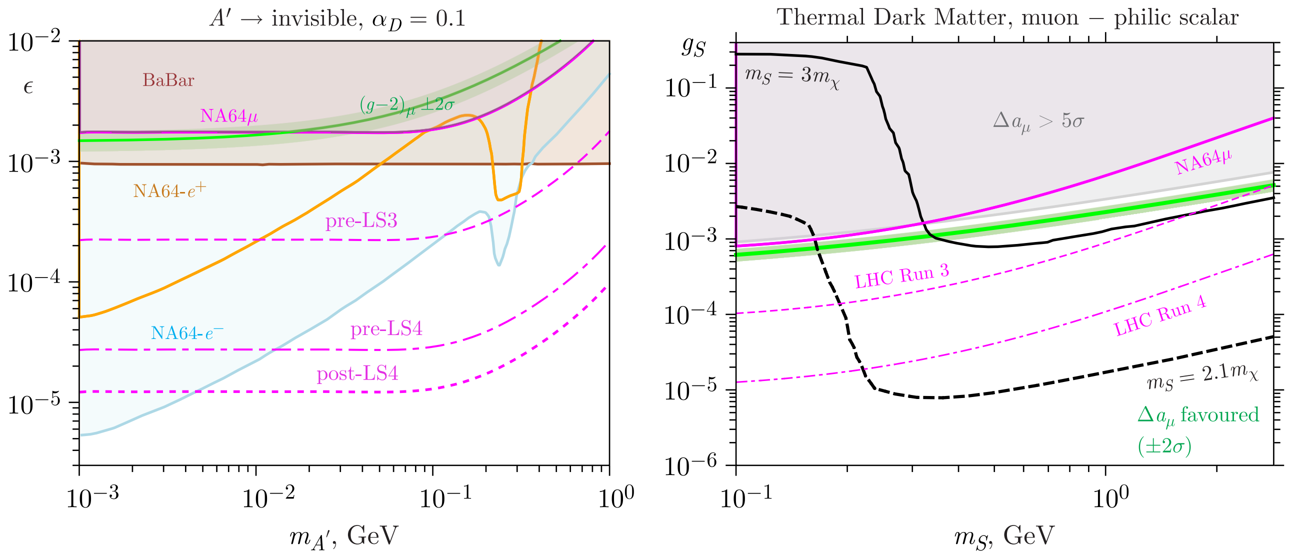

Figure 6. NA64μ 90% C.L. excluded limits with 1.98×10^{10} MOT and projected limits for the LHC Runs 3 and 4 for a Dark Photon (left) and for a muonphilic scalar mediator S (right) [54].

These limits are the first ones obtained using a high-energy muon beam [3]. These results open a new path to explore DS physics in a complementary way to present and future experiments, highlighting the robustness of our novel missing energy-momentum technique, which is planned to be used by other experiments such as LDMX and M3 [56, 57]. The results have been published in *Phys. Rev. Lett.* and have been featured in the *Physics Magazine of the American Physical Society* (APS) [3].

The projected sensitivities from the muon experimental program before the CERN Long Shutdown (LS3), or LHC Run 3, and after LS3, LHC Run 4 are also shown in Figures 5–7. For example, as shown in Figure 7, the full coverage of the parameter space of benchmark LDM models from combined results obtained with electron, positron and muon beams is expected.

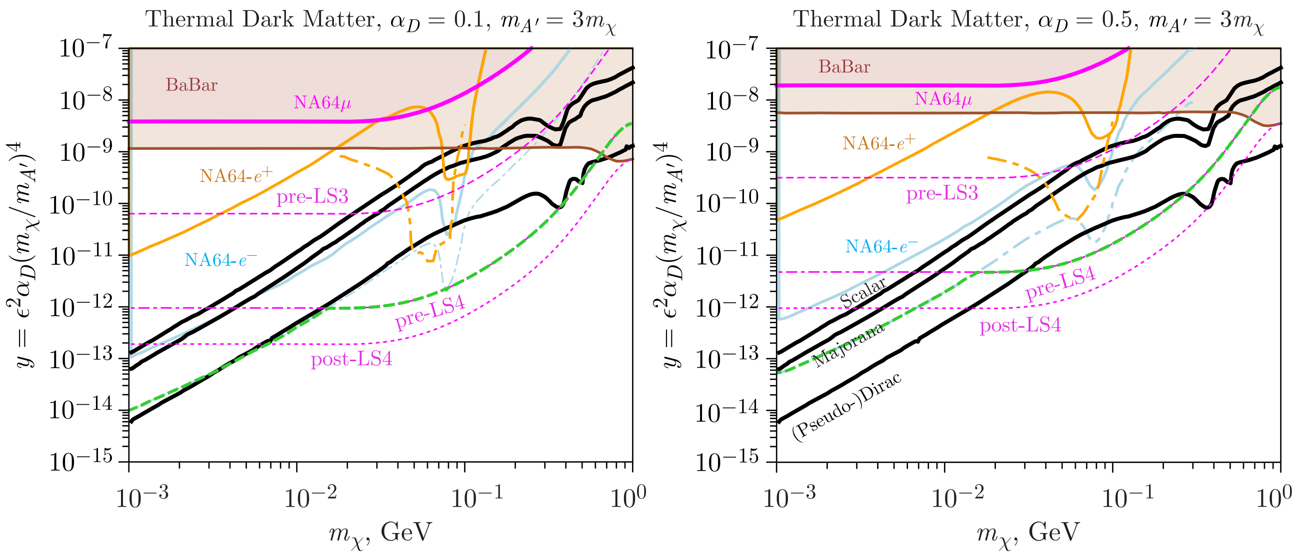

Figure 7. Combined NA64 90% C.L. excluded limits with 1.98×10^{10} MOT and projected limits for Light Dark Matter mediated by a Dark Photon.

The computation of those limits is based on the foreseen detectors' upgrade to cope with higher beam intensities and the background reduction due to improvement of the experimental set-up configuration that was already implemented in 2023–2024 data taking. The total statistics was improved by a factor of 20 compared to the 2022 pilot run. The preliminary results are encouraging, showing that the main background source arising from momentum miss-reconstruction could be reduced by two orders of magnitude and the tracking efficiency was improved by a factor of four. During LS3, further upgrades will be required to cope with the very high intensity that is potentially available at M2. Those include improving the detector hermeticity, adding new trackers, upgrading the calorimeters and trackers readout, and developing a new trigger scheme. Those improvements can also expand our scientific goals, and we plan to study our sensitivity to scenarios such as ALPs.

7. Summary

The search for dark sector physics and dark matter using the fixed-target NA64 experiment at the CERN SPS spans nearly a decade of remarkable progress. Being approved in 2016 for the LDM search with the pioneering active beam dump plus missing energy techniques at electron beam [1], NA64 since then has developed its application for incisive exploration of dark sectors with positron [2], muon [3], and, recently, hadron [4] beams. The experiment has successfully met its primary objectives, as outlined in the EPPS input (2018), producing results which demonstrate its potential for a high-sensitivity search for Dark Sectors and LDM and its ability to operate in a near-background-free environment. It has also exceeded its primary goals and, without compromising the searches for LDM, provides important inputs for other BSM scenarios. The PBC and FIPs communities recognize the high scientific value of NA64's contributions and its complementarity to other ongoing and planned experiments and support its continued exploration.

With the improvement of the SPS performance after LS3, we anticipate a great opportunity for the further sensitive exploration of the dark sector and other important new physics. To fully exploit its physics potential, NA64 will undergo an upgrade during LS3 to continue running in background-free mode at the higher SPS beam rates. Planned upgrades include (a) improved detector hermeticity with a new veto hadron calorimeter, (b) enhanced particle ID with a synchrotron radiation detector, and (c) increased beam rates via upgraded electronics. For NA64h, the best location is under study, including the PS T9 beamline, while true muonium production at H4 is being optimized. With the recently strengthened NA64 collaboration, stable operations and timely data analysis are planned for LHC Run 4.

With projected statistics of $\sim 10^{13}$ electrons, $\sim 10^{11}$ positrons (40 and 60 GeV), and $\sim 2 \times 10^{13}$ muons on target, NA64 aims to reach a sensitivity of $\lesssim 10^{-13}$ for dark sector searches. This will open access to uncharted LDM parameter space and other well-motivated models, enabling either discovery or conclusive exclusion.

Conflicts of interest

The authors declare no conflicts of interest.

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