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Status and prospects of the NA64 experiment

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The NA64 experiment at the CERN SPS has obtained the world-leading constraints in the search for Light Dark Matter (LDM) candidates with sub-GeV masses using an electron beam. Most recently, the complementarity of the physics case with the NA64e^{+} and NA64μ programs has been established, in particular following the first results for searches with high-energy muons. Planned upgrades for all programs during the CERN's next long shutdown (LS3) are aimed at boosting the experiment data-taking capabilities and ensuring a low level of background, further enhancing the sensitivity to the uncharted region of the parameter space suggested by benchmark LDM models. Finally, the feasibility of Dark Sector (DS) searches with hadronic beams, NA64h, has been demonstrated, opening a new avenue for exploration.

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1. LDM searches at the intensity-frontier

Despite extensive, large-scale efforts by the scientific community, the nature of Dark Matter (DM) remains a mystery [1]. Among the predictive theoretical frameworks that provide viable DM candidates, thermal relic models stand out as the observed DM abundance Ω_{DM} sets compelling targets for experiments. Assuming a thermal equilibrium between DM and SM in the very early Universe, freeze-out models require the annihilation cross-section to drive the depletion of the DM density to the observed value. Therefore, the condition $\Omega_\chi \approx \Omega_{DM}$ sets a constrain on the combination of DM mass m_χ and coupling strengths [2].

A broad class of Dark Sectors (DS) models introduces new, feebly interacting forces, extending beyond the paradigm of Weakly Interacting Massive Particles (WIMPs). These interactions, also referred to as portals, open the possibility of DM candidates with masses below the electroweak scale [3]. Such models can also address various unresolved SM puzzles such as the muon anomalous magnetic moment $(g-2)_\mu$ and the origin of neutrino masses. In the benchmark case of a vector mediator or Dark Photon, A', the annihilation rate of Light Dark Matter (LDM) candidates into SM through the s-channel process $\chi + \chi \to SM + SM$ can be described as:

$$\langle \sigma v \rangle_\chi \propto \varepsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \tag{1}$$

where $\langle \sigma v \rangle_\chi$ corresponds to the thermally-averaged annihilation cross-section, ε describes the kinetic mixing between the SM photon and the Dark Photon, and α_D is the coupling between χ and A'. Following the constraints on the annihilation cross-section from the thermal history, so-called thermal targets describe a direct correlation between the m_χ and the dimensionless parameter y that define well-motivated regions of interest for searches for Light Dark Matter (LDM) in the MeV−GeV range [4].

The feeble interaction strength in Dark Sectors naturally motivates experiments with access to high-intensity beams. Leveraging the high-purity beams at the CERN Super Proton Synchrotron (SPS), the fixed-target experiment NA64 has pioneered the searches for Dark Sector physics below the electroweak scale with missing-energy techniques in an active beam dump configuration [5]. Recently, the experiment has expanded its reach by incorporating new approaches using positron [6], muon [7] and hadron beams [8], maintaining the same core detection strategy. Unlike experiments that rely on DM scattering signatures, NA64 is less dependent on the specific nature of the DM candidate, allowing it to test a wide range of models. Moreover, its signal rate, which scales as ε^2, is enhanced over traditional beam dump experiments where the rate is suppressed by an additional factor of $\alpha_D \varepsilon^2$.

2. Missing energy/momentum searches in NA64

The experimental principle of NA64 consists of producing new DS mediators through the interaction of the high-energy particles scattering with the target nuclei. The presence of a new mediator is then inferred from the missing energy/momentum carried away by the final state DM particles. Fig. 1 illustrates the case of Dark Photon production with electrons via the radiative reaction $e^- \mathcal{N} \to e^- \mathcal{N} A'$, or through resonant annihilation of secondary positrons from the electromagnetic (e-m) shower $e^- e^+ \to A'$. When switching the beam polarity, the annihilation channel is enhanced by the primary positron contribution. Depending on the model and the mass hierarchy therein, the A' decays to either LDM particles that escape the detector or SM particles. In the former, a large fraction of the initial energy goes missing as the DM particles leave the setup undetected. On the other hand, scenarios with visible decays to SM would result in displaced vertex signatures, if the mediator is sufficiently long-lived. This is in particular the case for an axion-like particle or mediators decaying into excited DS states, and can be also probed at NA64 [9, 10]. A similar principle applies in the case of a high-energy muon beam, in which the signature is characterized by a scattered muon with missing momentum. Overall, the LDM searches at NA64 rely on the detection of the impinging beam particles on the target, requiring a clear definition of its incoming track and the effective containment of the interactions inside the target.

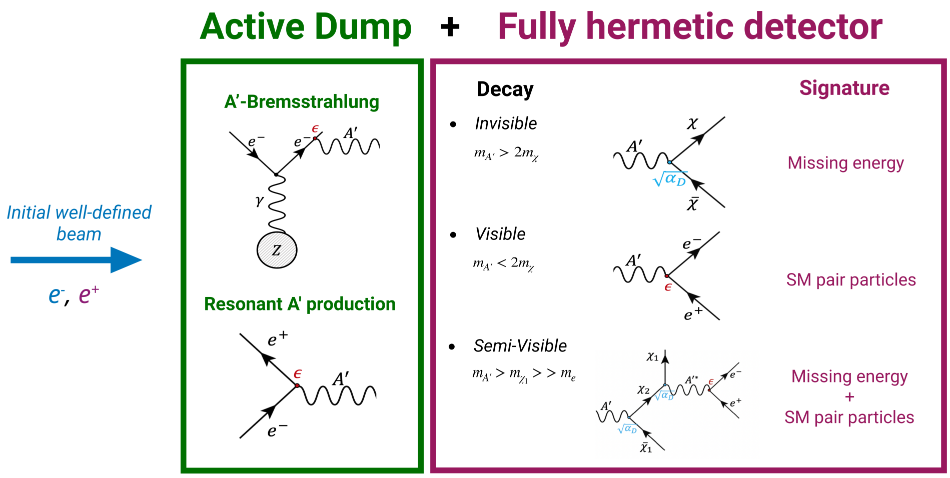

Figure 1: Sketch of the production and detection of A' at NA64 using electron or positron beams impinging on an active target. The resulting signatures in the three depicted scenarios can then be resolved exploiting the hermeticity of the detector.

3. NA64 latest results and status

NA64e^-

As the flagship program, the electron beam searches at H4 lead the global searches for LDM in the sub-GeV mass range. Having found no trace of any signal-like events in 9.37×10^{11} electrons on target (EOT), NA64 has been able to place the current most stringent exclusion limits in case of an invisibly-decaying new vector boson for the mass range $m_\chi \approx 1\,\text{MeV} - 100\,\text{MeV}$ [5], as illustrated in Fig. 3. At present, the on-going analysis on the combined 2023-2024 dataset (9.5×10^{11} EOT) aims to deliver a significant increase in the yield, as it doubles the published statistics. Furthermore, since the current sensitivity is limited by the integrated beam luminosity, recent efforts have been centered around the preparations for the runs after LS3. This includes the latest study of NA64 on the improved hermeticity of the 2023 setup using a large veto hadron calorimeter (VHCAL), motivating the development of a full-scale VHCAL to suppress the background from escaping hadrons produced upstream of the target [11]. Moreover, upgrades to the front-end electronics and DAQ are also underway, improving the rate capabilities of the system.

NA64e^+

Last year, NA64 published the first LDM results using a 100 GeV positron beam, paving the way of a complementary search that exploits the enhanced sensitivity obtained through the resonant annihilation production [6]. Most recently, the analysis of a dataset with a 70 GeV positron beam has been completed [12]. The next steps in the program include running at lower beam energies, providing an effective sweep over the LDM parameter space [13]. A critical upgrade in this context is the new LYSO-based SRD, with a prototype successfully tested in 2024. This ensures the efficient tagging of electrons at lower beam energies based on the emitted synchrotron radiation, which scales with the E^4.

NA64μ

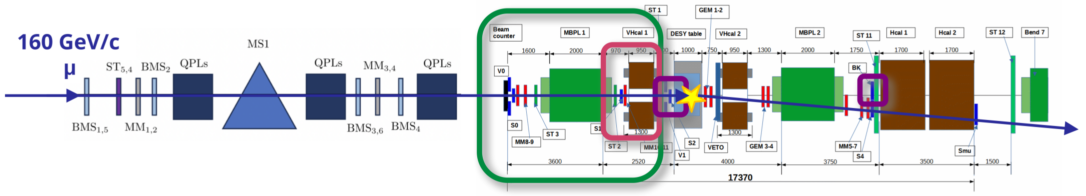

Figure 2: The NA64μ setup during the 2023 run at the M2 beamline. The signature is characterized by a scattered muon with missing momentum from the production of a new particle in the target. As part of the upgrades the setup features an additional VHCAL module (red), a new magnetic spectrometer (green) and scintillator counters (violet) are highlighted.

The first results on LDM searches with a high-energy muon beam have been published [7, 14]. The successful operation in 2023 and 2024 included important improvements in the setup, delineated in Fig. 2. These include an additional VHCAL module, aimed at suppressing the background from muon-nuclear interactions that could leak in the hermeticity of the detector. Furthermore, 8 new trackers were added to the detector, increasing the tracking efficiency in the downstream section as well as enabling the construction of an additional magnetic spectrometer (MS1). Lastly, the tagging of the scattered muons was improved by increasing the number of scintillators in the telescope. The analysis of a dataset collected with the improved setup and containing almost 15 times more statistics than the published results is on-going. Preliminary results are encouraging, clearly showing improvements in the momentum reconstruction and background suppression.

NA64h

Finally, a proof of principle for searches with hadron beams at CERN has been published, following a successful test run during 2022 [8]. Based on the same missing-energy approach, rare decays of neutral pseudo-scalar SM mesons are explored, enabling NA64 to probe models with coupling to quarks. With 2.9×10^9 pions-on-target collected in 2022, bounds on the invisible decays of η and η' were set, matching and even surpassing in the case of η' the previous limits set by BESIII [15]. The possibility of a test run at the T9 beamline in the CERN PS facility is under consideration. An addendum to the SPSC for the inclusion to the NA64 program is in preparation for the future plans.

4. Outlook

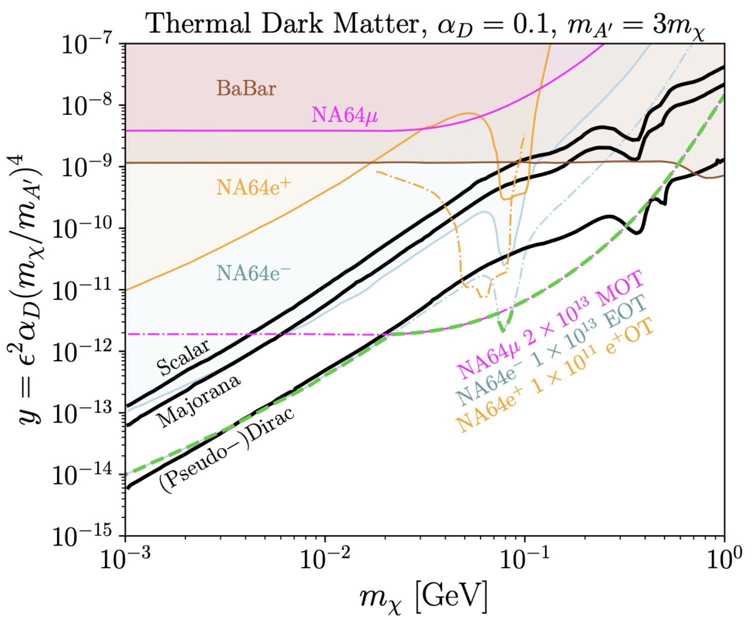

Figure 3: Current and future sensitivity of NA64 to the Dark Photon scenario $A' \to$ invisible in the (m_χ, y) parameter space including the thermal targets for scalar, Majorana and Pseudo-Dirac DM. Depicted are the 90% exclusion limits for the exploration with e^- (solid light blue line), e^+ (solid yellow line) and μ (solid pink line) beams [7]. The combined sensitivity is displayed as a green dashed line and is obtained from the projections of the individual programs (dash-dotted lines with the respective colors) for the statistics to be collected during the LHC Run 4.

NA64 has already delivered important results in the searches for LDM below the electroweak scale. The combined 2023-2024 dataset with 2 times more data for the electron and 15 times more for the muon programs are being analysed. Building on recent milestones, key areas requiring upgrades have been identified, and consequently these improvements are planned to be implemented during LS3 [16]. Additionally, the new hadronic program NA64h was successfully demonstrated, with a possible dedicated test run in 2025. As shown in Fig. 3, NA64 multi-pronged approach is well-positioned to conclusively discover or disprove compelling LDM models in the coming years, complementing the global efforts in the search for Dark Matter.

Acknowledgments

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