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Prospects for exploring the Dark Sector physics and rare processes with NA64 at the CERN SPS

The NA64 Collaboration[1]

Abstract:
The CERN SPS offers a unique opportunity for exploring new physics due to the availability of high-quality and high-intensity secondary beams. In the 2016-18 runs, the NA64 experiment has successfully performed sensitive searches for Dark Sector and other rare processes in missing energy events using high energy electron interactions in an active dump. The NA64 Collaboration plans to continue such searches to fully exploit the potential of the experiment and increase its discovery reach with high-energy muon and hadron beams. Our research program with e^- - beam aims at a high sensitivity search for visible and invisible decays of dark photons, A', and the exploration of the parameter space for the sub-GeV Dark matter production in invisible decays of A' mediator motivated by thermal Dark Matter models. It also includes clarification of the origin of the ^{8}Be anomaly, observed by the Atomki experiment, and searches for Axion Like Particles (ALP) particles. With the M2 muon beam, we propose to focus on the unique possibility to search for new states weakly coupled predominantly to muons, in particular a new gauge Z_μ boson of $L_\mu - L_\tau$ symmetry, which can resolve the long standing muon (g-2)$_\mu$ discrepancy. Further, more sensitive searches for the Z_μ as a vector mediator of Dark Matter production, LFV $\mu - \tau$ conversion and millicharged particles are also planned. Finally, the program includes probing Dark Sector with π, K beams, by looking for invisible decays $\pi^0, \eta, \eta', K^0_S, K^0_L \to invisible$ of neutral mesons, which is complementary to the current CERN program in the kaon sector.

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Contents

1 Introduction

Despite the intensive searches at the LHC and in non-accelerator experiments Dark Matter (DM) still is a great puzzle. One difficulty so far is that DM can be probed only through its gravitational interaction. Several theoretical ideas motivate the concept of Dark Sectors consisting of $SU(3) \times SU(2) \times U(1)$ singlet fields. The possibility of a Dark Sector that includes not only DM, but e.g. a dark photon A', mediating a dark sector $U(1)_D$ force, and other states has attracted a great deal of attention in recent years [1–6]. In particular, it has been noted that the A' of mass $m_{A'} < 1$ GeV may explain potential astrophysical signals of DM [7]. It was pointed out, that a dark state weakly coupled to muon could resolve the longstanding muon (g-2)$_\mu$ anomaly [8, 9], and moreover serve as a mediator of Dark Matter production [10–12]. This has motivated a worldwide experimental and theoretical effort towards dark forces and other portals between the visible and dark sectors, see Refs. [1–4, 13] for a review.

The NA64 was designed as a hermetic general purpose detector with a wide program of searches for Dark Sector physics and other rare processes in missing energy events from the electron, muon and hadron interaction in an active target [14, 15]. The experiment was approved in 2016 for running with electron beam and has already provided a few important results on probing the muon (g-2)$_\mu$ and ^{8}Be* anomalies [16, 17] , and by putting stringent constraints on vector mediator of Dark Matter production [18].

2 Research program at the H4 electron beam

In a class of models a new force between the dark and visible matter can be transmitted by a new vector boson, A' , called dark photon, of mass $m_{A'} \lesssim 1$ GeV. The A' couples to the standard model (SM) via the kinetic mixing term $\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$ with the ordinary photon parameterized by the

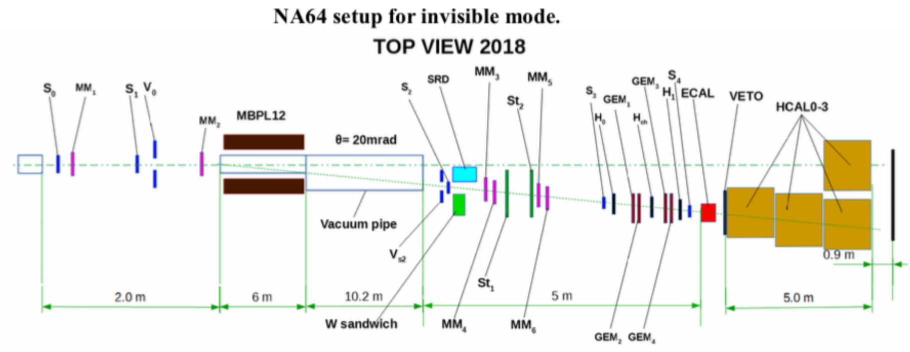

Figure 1. Schematic illustration of the setup to search for $A' \to invisible$ decays of the bremsstrahlung A's produced in the reaction $eZ \to eZA'$ of 100 GeV e$^-$ incident on the active ECAL target.

mixing strength ϵ. The mixing term results in the interaction $\mathcal{L}_{int} = \epsilon e A'_\mu J^\mu_{em}$ of dark photons with the electromagnetic current J^μ_{em} with a strength ϵe, where e is the electromagnetic coupling and $\epsilon \ll 1$.

Since there are no firm predictions for the A', its experimental searches have been performed over a wide range of A' masses and decay modes. If the A' is the lightest state in the dark sector, then it would decay mainly visibly, i.e., typically to SM leptons l (or hadrons) which can be used to detect it. However, in the presence of light dark states χ, in particular, DM with the masses $m_\chi < m_{A'}/2$, the A' would predominantly decay invisibly into those particles provided that coupling $g_D > \epsilon e$. Various dark sector models motivate sub-GeV scalar and Majorana or pseudo-Dirac fermion DM coupled to dark photons. To interpret the observed abundance of thermal relic density, the requirement of the thermal freeze-out of DM annihilation into visible matter through $\gamma - A'$ kinetic mixing allows one to derive a relation among the parameters $\alpha_D \simeq 0.02 f \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{m_{A'}}{100\ MeV}\right)^4 \left(\frac{10\ MeV}{m_\chi}\right)^2$ and $y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$, where $\alpha_D = e_D^2/4\pi$, $f \lesssim 10$ for a scalar, and $f \lesssim 1$ for a fermion [3]. This prediction combined with the fact that the intrinsic scale of the dark sector could be smaller than, or comparable to, that of the visible sector, provide an important target for the (ϵ, $m_{A'}$), (y, $m_{A'}$), (α_D, $m_{A'}$), parameter space which can be probed with the NA64 detector at energies attainable at the CERN SPS [14, 15].

2.1 The NA64 experiment

The NA64 is specially designed as a hermetic general purpose detector to search for dark sector physics in missing energy events from high-energy electron, muon, and hadron scattering off nuclei in an active dump. The method of the search can be illustrated by considering, as an example, the search for the vector mediator, e.g. the dark photon A', of Dark Matter (χ) production in invisible decay mode, $A' \to \chi\overline{\chi}$ [14, 15]. If the A' exists it could be produced via the kinetic mixing with bremsstrahlung photons in the reaction of high-energy electrons absorbed in an active beam dump (target) followed by the prompt $A' \to invisible$ decay into DM particles in a hermetic detector [19, 20]:

$$e^- Z \to e^- Z A'; A' \to invisible. \tag{2.1}$$

A fraction f of the primary beam energy $E_{A'} = f E_0$ is carried away by χ particles, which penetrate the target and detector without interactions resulting in zero-energy deposition. The remaining part of the beam energy $E_e = (1 - f)E_0$ is deposited in the target by the scattered electron. The occurrence of the A' production via the reaction (2.1) would appear as an excess of events with a signature of a single isolated electromagnetic (e-m) shower in the active dump with energy E_e

accompanied by a missing energy $E_{miss} = E_{A'} = E_0 - E_e$ above those expected from backgrounds. Here, it is typically assumed that in order to give a missing energy signature the χs have to traverse the detector without decaying visibly.

Compared to the traditional beam dump experiment the main advantage of the NA64 approach is that its sensitivity is proportional to the ϵ^2 associated with the particle production in the dump in the primary reaction followed by its prompt invisible decay into light (sub-GeV) dark matter particles. However, for the beam dump method the sensitivity is typically $\simeq \epsilon^4$, where one ϵ^2 comes from the new particle production in the dump, and another ϵ^2 is from the particle interaction in a far detector.

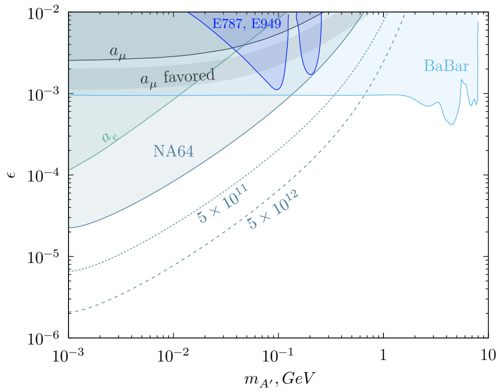

Figure 2. The NA64 90% C.L. exclusion regions in the $(m_{A'}, \epsilon)$ plane: the current (dashed blue) from Ref.[18], and expected for the accumulated number of 5×10^{11} EOT and 5×10^{12} EOT assuming background free case. Both constraints from NA64 and BaBar [24], rule out the A' parameter space explaining the muon g-2 anomaly, leaving, however, a significant area that is still unexplored. Limits from E787 and E949 experiments [1], as well as the muon α_μ favored area are also shown. Here, $\alpha_\mu = \frac{g_\mu - 2}{2}$.

Currently, NA64 employs the 100 GeV electron beam from the H4 beam line at the North Area of the CERN SPS with the maximal intensity up to $\gtrsim 10^7$ e^- per SPS spill. The NA64 detector is schematically shown in Fig. 1. The setup utilized the beam defining scintillator (Sc) counters S1-S3 and veto V1, and the spectrometer consisting of two successive dipole magnets with the integral magnetic field of $\simeq$7 T·m and a low-material-budget tracker, which is a set of Micromegas (μM), GEM and Straw tube (St) chambers [21, 22]. The magnets also served as an effective filter rejecting the low energy electrons present in the beam. The key feature of NA64 is the detection of the the synchrotron radiation (SR) from high energy electrons in the magnetic field with the SR detectors (SRD) to significantly enhance electron identification and suppress background from the hadron contamination in the beam, as shown schematically in Fig. 1. This allowed to additionally suppress the initial level of the hadron contamination in the beam $\pi/e^- \lesssim 10^{-2}$ by more than 4 orders of magnitudes [23]. The detector is also equipped with an active target, which is a hodoscopic electromagnetic calorimeter (ECAL) for the measurement of the energy (E_{ECAL}) of the recoil electron from the reaction (2.1), as well as the X, Y coordinates of the incoming electrons by using the transverse e-m shower profile. A high-efficiency veto counter $VETO$, and a massive, hermetic hadronic calorimeter (HCAL) of $\simeq$ 30 nuclear interaction lengths (λ_{int}) were positioned just after the ECAL and served as an efficient veto to detect muons or hadronic secondaries produced in the e^-A interactions in the ECAL target. The setup shown in Fig.1 allows also searching for the A' decaying into e^+e^- pairs, see Sec. 2.4. The first results obtained in 2016-2017 for both $A' \to invisible$ and $A' \to e^+e^-$ decay modes, reported in Ref.[16–18], confirm the validity and sensitivity of the NA64 technique for searching for dark sector physics.

2.2 Search for the $A' \to invisible$ decays

The obtained [16, 18] and expected NA64 90% C.L. exclusion limits on the mixing strength as a function of the A' mass are presented in Fig. 2. The limits are obtained with a full NA64 detector simulation [19] and by using the A' production cross section obtained with the exact tree-level calculatioins [20]. The NA64 bounds are the best for the mass range $0.001 \lesssim m_{A'} \lesssim 0.1$ GeV. The constraints obtained from direct searches of $A' \to invisible$ decays in the BaBar [24], E787 and E949 experiments [1] are also shown.

2.3 The NA64 constraints and projections for sub-GeV Dark Matter

The NA64 limits obtained from the full data sample of the 2016-17 run and future projections are shown in the left panel of Fig. 3 together with the favoured parameters for scalar, pseudo-Dirac (with a small splitting) and Majorana scenario of LTDM taking into account the observed relic DM density [3]. The limits are calculated under the conventional assumption $\alpha_D = 0.1$ and $\alpha_D = 0.005$, and $m_{A'} = 3m_\chi$, here m_χ stands for the LTDM particle's masses, either scalars or fermions. The

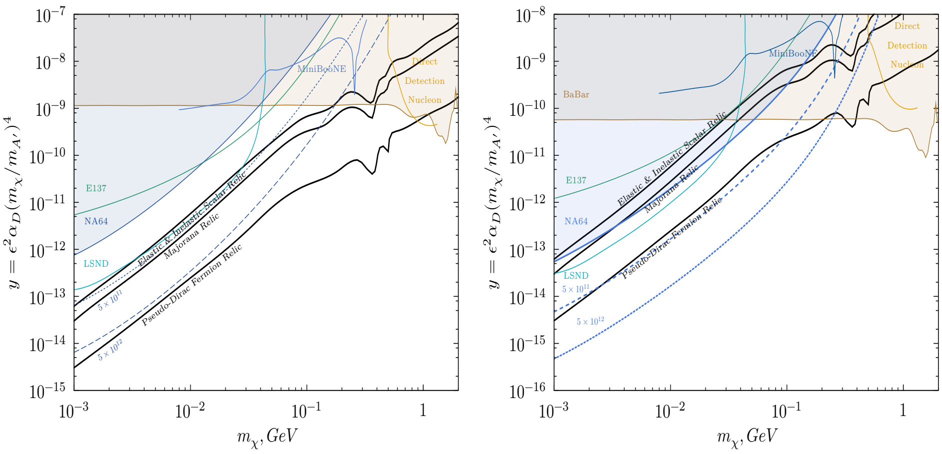

Figure 3. The NA64 limits in the (y;m_χ) plane obtained for $\alpha_D = 0.1$(left panel) and $\alpha_D = 0.005$(right panel)and from the full 2016 data set [18] and expected for 5×10^{11} EOT and 5×10^{12} EOT assuming background free case. The limits are shown in comparison with limits from other experiments. The favoured parameters to account for the observed relic DM density for the scalar, pseudo-Dirac and Majorana type of light thermal DM are shown as the lowest solid line.

plot shows also the comparison of our results with limits from other experiments. It should be noted that differently from the results of beam dump experiments, such as LSND, E137, MiniBooNE [25], the χ-yield in our case scales as ϵ^2, not as $\epsilon^4 \alpha_D$. Therefore, for sufficiently small values of α_D our limits will be much stronger. This is illustrated in the right panel of Fig. 3, where the NA64 limits and bounds from other experiments are shown for $\alpha_D = 0.005$. One can see, that for this, or smaller, values of α_D, the direct search for the $A' \to invisible$ decay in NA64 excludes model of scalar and Majorana DM production via vector mediator for the remaining mass region $m_\chi \lesssim 0.05$ GeV. While being combined with the BaBar limit [24], the result excludes the model for the entire mass region $m_\chi \lesssim 1$ GeV.

The experimental upper bounds on ϵ also allow to obtain lower bounds on coupling constant α_D which are shown in Fig. 4 in the (α_D;m_χ) plane [3]. This choice of parameters , instead of presentation in the (y;m_χ) plane, is more preferable for NA64 because unlike beam dump experiments the NA64 limits on the mixing strength do not depend on the coupling α_D. For the mass range

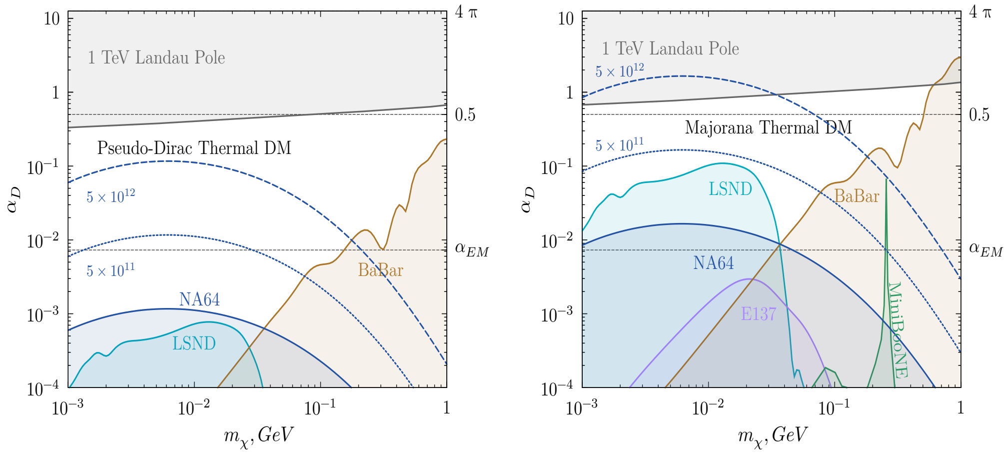

Figure 4. The NA64 constraints in the (α_D;$m_{A'}$) plane on the pseudo-Dirac (the left panel) and Majorana (right panel) type light thermal DM f[3] obtained from the full 2016-17 data set [18] and expected for 5×10^{11} EOT and 5×10^{12} EOT. The limits are shown in comparison with bounds from from the results of the LSND and E137 from Ref.[3], BaBar [24] and MiniBooNE [25] experiments.

$m_\chi \lesssim 0.05$ GeV the obtained bounds are more stringent than the limits obtained from the results of LSND and E137 [3].

2.4 The ^{8}Be-anomaly: a new $X(17)$ gauge boson? The visible $A' \to e^+e^-$ decays

The ATOMKI experiment of Krasznahorkay et al. [26] has reported the observation of a 6.8 σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the nuclear transitions of excited $^8Be^*$ to its ground state via internal pair creation. This anomaly can be interpreted as the emission of a new protophobic gauge X boson with a mass of 16.7 MeV followed by its $X \to e^+e^-$ decay assuming that the X has non-universal coupling to quarks, coupling to electrons in the range $2 \times 10^{-4} \lesssim \epsilon_e \lesssim 1.4 \times 10^{-3}$ and the lifetime $10^{-14} \lesssim \tau_X \lesssim 10^{-12}$ s [27].

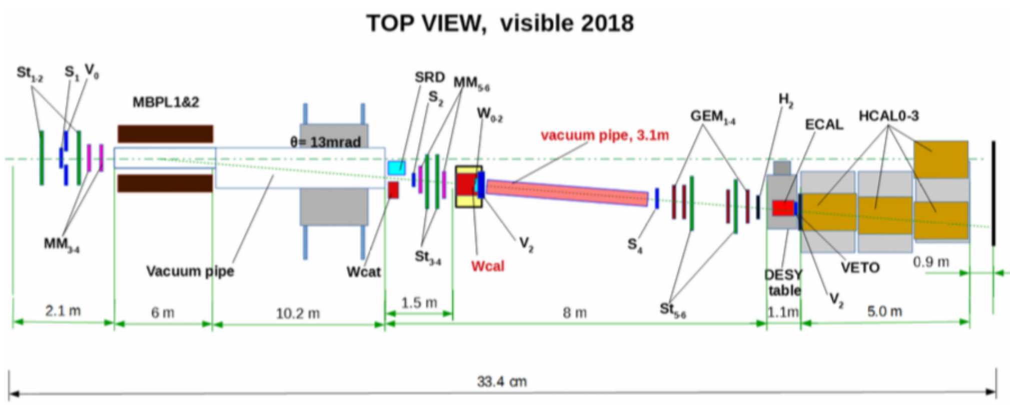

Figure 5. Schematic illustration of the setup to search for $A' \to invisible$ decays of the bremsstrahlung A's produced in the reaction $eZ \to eZA'$ of 100 GeV e$^-$ incident on the active ECAL target.

The NA64 setup for the visible A', X decays is schematically shown in Fig. 5. Downstream of the SRD detector an active dump (WCAL), a compact tungsten e-m calorimeter is installed. It was made as short as possible to maximize the sensitivity to short lifetimes while keeping the shower leakage small. The method of the search for $A' \to e^+e^-$ decays is described in [14, 15]. If the A' exists, due to the $A'(X) - e^-$ coupling it would occasionally be produced by a shower electron (or positron) in its scattering off a nuclei of the WCAL dump:

$$e^- + Z \to e^- + Z + A'(X); \; A'(X) \to e^+e^-. \tag{2.2}$$

Since the A' is penetrating and enough longer lived, it would escape the beam dump, and subsequently decays into an e^+e^- pair in a downstream set of detectors. The pair energy would be equal to the energy missing from the dump. The apparatus is designed to identify and measure the energy of the e^+e^- pair in another calorimeter (ECAL). Thus, the signature of the $A'(X) \to e^+e^-$ decay is an event with two e-m-like showers in the detector: one shower in the dump, and another one in the ECAL with the sum energy equal to the beam energy. The NA64 90% C.L. exclusion limits on the mixing ϵ as a function of the A' mass is shown in Fig. 6 together with the current constraints from other experiments. Our results exclude X-boson as an explanation for the ^{8}Be* anomaly for the $X - e^-$ coupling $\epsilon_e \lesssim 4.2 \times 10^{-4}$ and mass value of 16.7 MeV, leaving the still unexplored region $4.2 \times 10^{-4} \lesssim \epsilon_e \lesssim 1.4 \times 10^{-3}$ as quite an exciting prospect for further searches. The NA64 projected sensitivity to the $A' \to e^+e^-$ decays is presented in the middle panel in Fig. 6 for the different number of accumulated EOT.

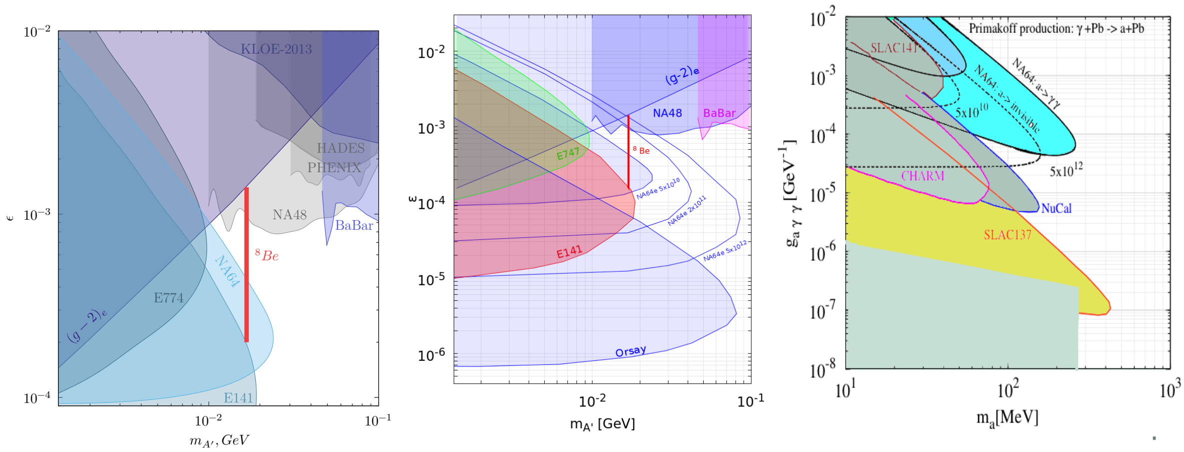

Figure 6. Left panel: The 90% C.L. exclusion areas in the $(m_X; \epsilon)$ plane from the NA64 experiment (blue area). For the mass of 16.7 MeV, the $X - e^-$ coupling region excluded by NA64 is $1.3 \times 10^{-4} < \epsilon_e < 4.2 \times 10^{-4}$. The allowed range of ϵ_e explaining the ^{8}Be* anomaly (red area) [27], constraints on the mixing ϵ from others experiments and bounds from the electron $(g-2)_e$ are also shown [3]. Middle panel: The 90% C.L. exclusion areas in the $(m_{A'}; \epsilon)$ plane from the NA64 experiment (blue curves) for the different numbers of EOT (indicated near the curves) accumulated at 150 GeV. Right panel: The projective NA64 constraints in the $(g_{\gamma\gamma}$ vs $m_a)$ plane on the ALP decaying as $a \to \gamma\gamma$ obtained for $5 \times 10^{11}, 5 \times 10^{12}$ EOT and shown in comparison with bounds obtained from the results of the E137 , E141, CHARM, and NuCal experiments, see Ref.[13]. Black solid lines: visible mode setup. Black dashed lines: invisible mode setup.

2.5 The $a \to \gamma\gamma$ and $a \to invisible$ decays of ALPs

The results from the 2017 run shows that NA64 is also capable of a sensitive search for the axion-like particles (ALP) that couple predominantly to two photons (or decaying invisibly). The idea is to use the detector shown in Fig.5 for searches of ALPs in events with the pure neutral e.m. final state detected in the ECAL. One can see from Fig. 6 (right pannel) that NA64 could cover the niche of short-lived ALPs decaying into two photons, $a \to \gamma\gamma$, corresponding to the parameter space $10^{-4} \lesssim g_{a\gamma\gamma} \lesssim 10^{-2}$ for the a-mass range $10 \lesssim m_a \lesssim 500$ MeV assuming accumulation of $n_{EOT} \simeq 5 \times 10^{12}$. The NA64 90% C.L. exclusion limits on the coupling $g_{a\gamma\gamma}$ as a function of the ALP mass is shown in Fig. 6 together with the current constraints from other experiments. The limits are calculated from simulations for the background free case and 30% for the signal efficiency.

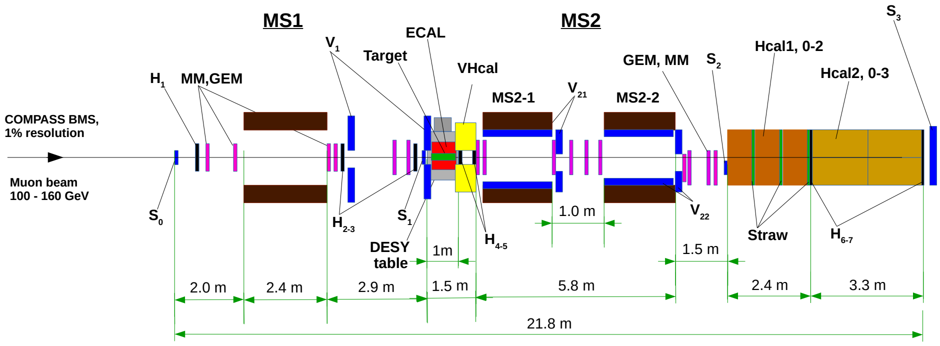

Figure 7. Schematic illustration of the setup to search for dark Z_μ. The bremsstrahlung Z_μs are produced in the froward direction in the reaction $\mu + Z \to \mu + Z + Z_\mu$ of a high-energy muon scattering off nuclei of an active target T. The target is surrounded by an ECAL serving as a veto against photons or other secondaries emitted at a large angle. A fraction $f \lesssim 0.5$, of the beam energy is carried away by the scattered muon, while the rest of the total energy is transmitted by the Z_μ decay neutrino through the T, the veto counters V1 and V2, and a massive hermetic HCAL.

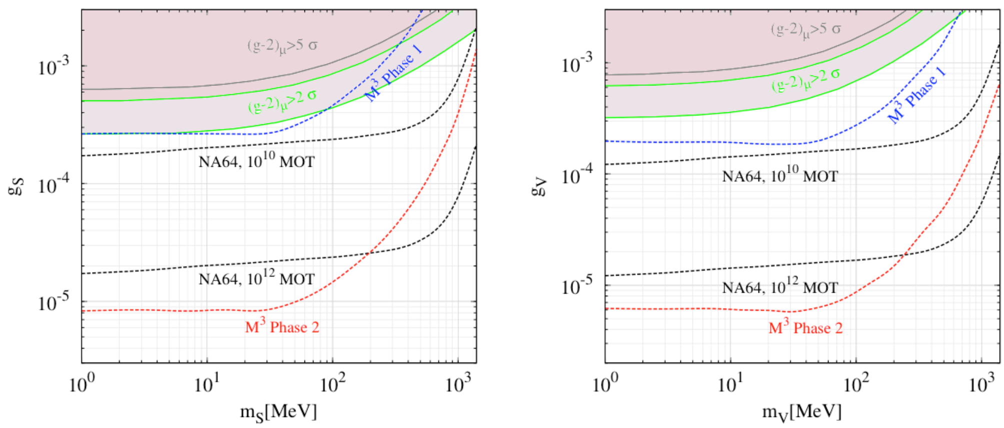

Figure 8. Parameter space for a muonc scalar S (left) or vector V (right) particle as described in Ref.[11, 28]. Left panel: the expected sensitivity for the search for dark scalar S interacting with the fermion as $L_S = g_S \bar{f} f$ in the experiments NA64μ [28] and M^3 [11] Right panel: the projected sensitivity to probe vector mediator coupled to SM fermions as $L_V = g_V V_\mu \bar{f} \gamma_\mu f$. It is assumed that both the S and V decay predominantly invisibly. The green bands represent the parameter space for which such particles can reconcile the (g-2)$_\mu$ anomaly to within 2σ of the measured value.

3 Plan of searches with the M2 muon beam

3.1 The muon $(g-2)_\mu$ anomaly and the new gauge boson Z_μ of $L_\mu - L_\tau$

The precise measurement of the anomalous magnetic moment of the positive muon $a_\mu = (g-2)/2$ from the Brookhaven AGS experiment 821 [8] gives a result which is about 3.6 σ higher than the

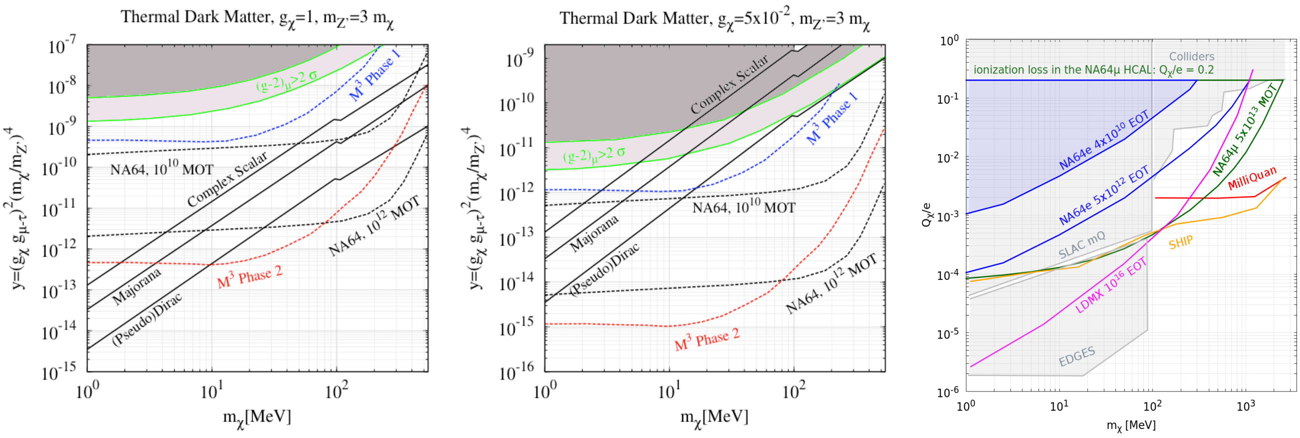

Figure 9. Parameter region for thermal DM charged under $U(1)_{L_\mu - L_\tau}$, for DM charges near the pertubativity limit (left), based on the running of the g_χ coupling arguments, or smaller g_χ values such that the (g-2)$_\mu$ region overlaps with the thermal relic curves (middle) [11]. Here the relic abundance occurs via direct annihilation to SM particles via s -channel Z' exchange. Left panel corresponds to enhanced DM coupling $g_\chi = 1$ to vector mediator Z', and right panel represents suppressed DM coupling $g_\chi = 5 \cdot 10^{-2}$. Right panel: The NA64 90% C.L. exclusion region in the $(m_Q, Q/e)$ plane expected for 5×10^{12} EOT and 5×10^{13} MOT assuming background free case.

Standard Model (SM) prediction

$$a_\mu^{exp} - a_\mu^{SM} = 288(80) \times 10^{-11} \tag{3.1}$$

This result may signal the existence of new physics beyond the Standard Model. Recently, the most popular new-physics explanation, a light (sub-GeV) dark photon with kinetic mixing $\epsilon \lesssim 10^{-3}$ and flavor-universal couplings, has been ruled out regardless of whether it decays visibly [3] or invisibly [16, 24]. The only remaining class of sub-GeV new-physics explanations involves particles that couple predominantly (or exclusively) to muons and tau lepton, thereby evading the limit from dark photon searches. A well motivated example of a such model is the Standard Model extension with the $U(1)_{L_\mu - L_\tau}$ gauge symmetry which predict the existence of a new massive gauge Z_μ boson coupled predominantly to the second and third lepton generations through the $L_\mu - L_\tau$ current. The mass of the Z_μ is currently constrained to be $m_{Z_\mu} \lesssim 200$ MeV, so its dominant decay is the invisible decay $Z_\mu \to \nu\nu$. In a well-motivated class of models, Dark Matter could interact predominantly with muons through a new force Z_μ carrier, which enables thermal freeze-out in the early universe. This scenario generally assumes sizeable couplings to visible particles and predictive experimental benchmarks, yet remains inaccessible to traditional DM searches. Such muon-specific forces are also well-motivated without any possible connection to Dark Matter. The persistent 3.6σ muon (g-2)$_\mu$ anomaly remains one of the puzzle in particle physics.Thus, a robust test of the new-physics hypothesis requires improved sensitivity to muonic forces.

3.2 The experiment NA64μ

The proposed extension of the experiment NA64, called NA64μ and shown in Fig. 7, is dedicated to a sensitive search for the Z_μ in the (g-2)$_\mu$ parameter space and Dark Matter particles (χ) production via the invisible decays $Z_\mu \to \chi\overline{\chi}$ with the Z_μ mass in the sub-GeV range. If the Z_μ exists, it could be observed in the reaction $\mu + Z \to \mu + Z + Z_\mu$ of a muon scattering off a nuclei by looking for an excess of events with a large missing muon energy in a detector due to the prompt bremsstrahlung Z_μ decay $Z_\mu \to$ *invisible*. The method of the search is illustrated in Fig. 7. The experimental technique and the feasibility study of the proposed search are described in details in Ref.[30]. We show that this specific signal allows a search for the Z_μ with a sensitivity to the coupling constant $\alpha_\mu \gtrsim 10^{-11}$, which is 3 orders of magnitude lower than the value required to explain the (g-2)$_\mu$ discrepancy. We point out that the availability of high-energy and high-intensity muon beams at the CERN SPS provides a unique opportunity either to discover or rule out the Z_μ in the near future. The NA64μ is based on the missing-energy approach developed for searching for the $A' \to invisible$ decays and is complementary to this experiment. The experiment has also a capability to search for invisible decays $S_\mu \to invisible$ of light scalars with a high sensitivity.

3.3 Projections for Z_μ mediator of Dark Matter production in invisible decay mode

The occurrence of Z_μ produced in $\mu^- Z$ interactions would appear as an excess of events with a single scattered muon accompanied by zero-energy deposition in the detector, shown in Fig. 7, above those expected from the background sources. In Fig. 2.5 and 9 the NA64 constraints on the scalar (g_V) and vector (g_V) couplings to muon as well as limits on the variable y are shown. The limits calculations [28, 30] assume a background free case and 50% efficiency for the signal.

3.4 Search for (pseudo)scalars, millicharged particles, and LFV $\mu - \tau$ conversion

For the case of pseudoscalars (P) coupled to muons and decaying invisibly, we assume that P decays dominantly into hidden particles. The NA64$_\mu$ exclusion region was estimated with simulations [28, 30]. The NA64 constraints on millicharged particles are shown in Fig. 9, see also Ref.[29, 30]. As the experimental signature for the milliQ particles production in the NA64 dump is identical to the one for the $Z_\mu, A' \to invisible$ decay search, the limits are estimated from the Z_μ signal simulation [29] for background-free case. The experiment is also capable for a sensitive search for the deep inelastic lepton-flavour violation (LVF) $\mu - \tau$ conversion on nuclei [31].

4 Probing Dark Sector in invisible decays of neutral mesons

In the standard model the rate of the $\pi^0, \eta, \eta', K_S, K_L \to \nu\overline{\nu}$ decays is predicted to be extremely small. Therefore, an observation of any of these mesons (M^0) decaying invisibly would unambiguously signal the presence of new physics [32]. For example, the M^0 could decay invisibly into a pair of heavy neutrinos [33], or disappear into Dark Sector [34]. The Bell-Steinberger relation connects CP and CPT violation in the mass matrix to CP and CPT violation in all decay channels of neutral kaons. It is a powerful tool for testing CPT invariance in the $K^0 - \overline{K^0}$ system, assuming that there are no significant undiscovered decay modes of either K_S or K_L which could contribute to the precision of the results. The $K_S, K_L \to invisible$ decays have never been tested and the question of how much these decays can influence the Bell-Steinberger analysis of the $K^0 - \overline{K}^0$ system still remains open. We propose a new experiment to search for the $M^0 \to invisible$ decays which aims at probing new physics and answering this question [32]. The experiment utilizes high-energy hadronic beams from the CERN SPS and the charge-exchange reactions of pions or kaons on nucleons of an active target, e.g. $\pi^-(K^-) + p \to M^0 + n$, as a source of the well-tagged M^0s emitted in the forward direction with the beam energy. If the decay $M^0 \to invisible$ exists, it could be observed by looking for an excess of events with a specific signature: the complete disappearance of the beam energy in the detector. This unique signal of $M^0 \to invisible$ decays allows for searches of the decays $K_S, K_L \to invisible$ with a sensitivity in the branching ratio $\mathrm{Br}(K_S(K_L) \to invisible) \lesssim 10^{-9}(10^{-7})$, and $\pi^0, \eta, \eta' \to invisible$ decays with a sensitivity a few orders of magnitude beyond the present experimental limits.

5 Summary

The CERN SPS offers a unique opportunity for exploring Dark Sector physics and other rare processes with the general purpose NA64 detector due to availability of high intensity secondary

Table 1. The NA64 research program: Projections for searches for Dark Sector physics and other rare processes with e, μ, π, K beams.

Process	New Physics	Comments, Projections for limits
e^- **beam**		Required number of EOT: 5×10^{12}
$A'\to e^+e^-$, and	Dark photon	$10^{-5}<\epsilon<10^{-2}$, $1\lesssim m_{A'}\lesssim 100$ MeV
$A'\to invisible$		$2\times10^{-6}<\epsilon<10^{-3}$, $10^{-3}\lesssim m_{A'}\lesssim 1$ GeV
$A'\to\chi\overline{\chi}$	sub-GeV Dark Matter (χ)	Scalar, Majorana, pseudo-Dirac DM
		$\alpha_D^{S,M}\lesssim 1$, $\alpha_D^{p-D}\lesssim 0.1$, for $m_\chi\lesssim 100$ MeV
$X\to e^+e^-$	new gauge X- boson	^{8}Be* anomaly, $\epsilon_e^{up}<10^{-5}$; $\epsilon_e^{low}>2\times10^{-3}$
milliQ particles	Dark Sector, charge quantisation	$10^{-4}<mQ<0.1$ e, $10^{-3}<m_{mQ}<1$ GeV
$a\to\gamma\gamma, invisible$	Axion-like particles	$g_{a\gamma\gamma}^{inv}\lesssim 2\times10^{-5}$, $m_a\lesssim 200$ MeV
μ^- **beam**		Required number of MOT: 10^{11} – 5×10^{13}
$Z_\mu\to\nu\nu$	gauge Z_μ-boson of $L_\mu-L_\tau$, $<2m_\mu$	(g-2)$_\mu$ anomaly; $g_\mu^V\lesssim 10^{-4}$, with $\lesssim 10^{11}$ MOT
$Z_\mu\to\chi\overline{\chi}$	$L_\mu-L_\tau$ charged Dark Matter (χ)	$y\lesssim 10^{-12}$ for $m_\chi\lesssim 300$ MeV with $\simeq 10^{12}$ MOT
milliQ	Dark Sector, charge quantisation	$10^{-4}<mQ<0.1$ e, $10^{-3}<m_{mQ}<2.5$ GeV
$a_\mu\to invisible$	non-universal ALP coupling	$g_Y\lesssim 10^{-2}$, $m_{a_\mu}\lesssim 1$ GeV
$\mu-\tau$ conversion	Lepton Flavour Violation	$\sigma(\mu-\tau)/\sigma(\mu\to all)\lesssim 10^{-11}$
π^-, K^- **beams**	Current limits, PDG'2018	Required number of POT(KOT):$5\times10^{12}(5\times10^{11})$
$\pi^0\to invisible$	$Br(\pi^0\to invisible)<2.7\times10^{-7}$	$Br(\pi^0\to invisible)\lesssim 10^{-9}$
$\eta\to invisible$	$Br(\eta\to invisible)<1.0\times10^{-4}$	$Br(\eta\to invisible)\lesssim 10^{-8}$
$\eta'\to invisible$	$Br(\eta'\to invisible)<5\times10^{-4}$	$Br(\eta\to invisible)\lesssim 10^{-7}$
$K_S^0\to invisible$	no limits	$Br(K_S^0\to invisible)\lesssim 10^{-9}$
$K_L^0\to invisible$	no limits	$Br(K_L^0\to invisible)\lesssim 10^{-7}$
		complementary to $K^-\to\pi\nu\nu$

beams. The recently concluded NA64 runs in 2016-2018 consisted of physics programs which address the two most important issues currently accessible with electron beam: a high sensitivity search for dark photon A' mediator of sub-GeV Dark Matter production in invisible decay modes and a search for visible decays of dark photon $A'\to e^+e^-$ and of a new 17 MeV gauge X-boson, $X\to e^+e^-$, which can resolve the anomaly observed in the excited ^{8}Be nuclei transitions. The incoming SPS runs 2021-23, combined with the 2016-18 runs, provides us with the opportunity to meet and perhaps exceed our original goals for the program with electron beam, and to start on a new physics program summarised in Table 1. Therefore, the NA64 Collaboration proposes to carry out further searches for Dark Sector particles and others rare processes in missing energy events from i high-energy electron interactions at H4 beam, and extend them to the M2 muon and hadron beams at the CERN SPS. Six months of running time at H4 line in 2021-23 will allows us to accumulate at least a factor 10 more statistics, $(3-5)\times10^{12}$ EOT, and to explore most of the sub-GeV Dark Matter parameter space, either to observe or completely rule out the 17 MeV gauge X-boson explanation of the ^{8}Be anomaly and put stringent bounds on the visible decays $A'\to e^+e^-$ of dark photons. For the M2 muon beam we propose to focus on the unique opportunity to discovery a new state, e.g. the Z_μ, weakly coupled predominantly to muon that could resolve the longstanding muon (g-2)$_\mu$ anomaly. Two months of running at M2 line will allow us to collect enough muons in order to get a conclusive result. We also propose to explore Dark Sector states in invisible decays $\pi^0,\eta,\eta',K_S^0,K_L^0\to invisible$ of neutral mesons with π, K beams.

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