Status and Plans for the NA64 Experiment

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Abstract. The NA64 experiment at the CERN North Area searches for dark matter production via both visible and invisible decays of sub-GeV vector mediators, such as the dark photon A'. In a first data taking period from 2016-2018, A' generation from the reaction e Z $\rightarrow$ e Z A' and subsequent decays $A' \rightarrow \chi\bar{\chi}$ and $A' \rightarrow e^+e^-$ was studied with the help of an active dump set-up using 100 GeV/c and 150 GeV/c electrons. Recently, an extension of the performed searches was proposed using a 150 GeV/c muon beam, available at the M2 beamline at CERN. These measurements would allow for additional coverage of parameter space towards higher A' masses and would open the possibility for searches for a new gauge boson Z_μ that would couple predominantly to the second and third lepton generations. We will present both the analysis of the available NA64 data as well as future plans for searches with muon and electron beams that are proposed within the "Physics Beyond Colliders" framework at CERN, including optimisation of the M2 optics and integration studies for implementing NA64μ in the EHN2 experimental area.

1. Introduction

Dark Sectors are naturally present in many theoretical models, usually identified with hypothetical particles that carry no charge with respect to the classical strong, weak, and electromagnetic forces, hence eliminating known shortcomings of the Standard Model (SM). These particles would interact at least gravitationally, but could also feebly interact with visible matter through so-called portals, classified by the spin and parity of the force mediator. The vector portal can be generated by adding a $U(1)_D$ symmetry to the SM $SU(3)_c \times SU(2)_L \times SU(1)_Y$ gauge group, introducing a "dark photon" A' as the mediator. The connection to the SM sector would then occur via "kinetic mixing", taking the form of a singlet operator with coupling strength ϵ that is assumed to be small, see e.g. Refs [1, 2]. Depending on its mass, the dark photon would either decay via an invisible channel to dark matter particles $\chi\bar{\chi}$ if the condition $M_{A'} \geq 2M_\chi$ is fulfilled or to SM particles via a visible channel for $M_{A'} < 2M_\chi$, for instance to e^+e^-. The latter channel is particularly interesting in view of the so-called ATOMKI anomaly describing an excess of events around 17 MeV/c^2 in the e^+e^- mass spectrum observed [3] in nuclear transitions of $^8Be^* \rightarrow {}^8Be\ \gamma$, $\gamma \rightarrow e^+e^-$, which could be explained by a vector boson X(17) with a mass of 16.7 MeV/c^2 [4].
The NA64 experiment was proposed [5] in December 2013 with the goal to explore the dark sector in the MeV/c^2 to GeV/c^2 mass range, mainly focusing on searches for the dark photon A' with an active beam-dump set-up. Both visible and invisible channels have been explored with electron beams in the recent data taking periods from 2016 to 2018 at the H4 beamline at CERN. In the context of the "Physics Beyond Colliders" framework at CERN, both upgrades of the existing electron beam experiment and an extension of the searches towards higher masses were proposed, respectively, the latter exploiting the M2 muon beam at CERN.

2. Searches for the Invisible Decay $A' \to \chi\bar{\chi}$

The NA64 set-up for searches in the invisible decay channels is depicted in Fig. 1. The secondary 100 GeV/c electron beam of the H4 beamline at the CERN SPS has a maximum intensity of about 10^7 electrons per 4.8 s extraction, typically every 20 s. It enters the set-up through trigger and veto scintillators (S1, V1) before it traverses two strong spectrometer magnets, which are surrounded by a set of Micromega and GEM trackers (T1–T4), providing a momentum resolution of 1%. The electrons are then tagged by a synchrotron radiation detector (SRD) and pass another set of trigger scintillators (S2, S3). The beam is impinging on a pre-shower detector and an electromagnetic calorimeter (ECAL) used as an active target. The set-up is completed by another scintillator veto detector (V2) and hadronic calorimeters providing about 28λ interaction length, interleaved with detectors for muon identification for maximum hermeticity. The set-up has been upgraded in 2018 by a slight re-arrangement of the HCAL modules together with adding large-area Straw trackers.

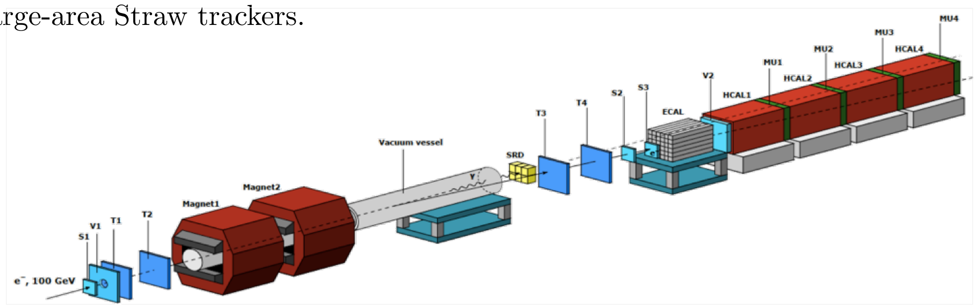

Figure 1. NA64 set-up for invisible decay searches.

The experimental signature for bremsstrahlung production and subsequent invisible decay of an A' candidate is a deposition of at most half of the incoming beam energy in the ECAL with no signal in both vetos and HCAL, as the rest is being carried away by the dark matter particles. In addition, both lateral and longitudinal shower shapes in the ECAL shall be consistent with electromagnetic showers. Possible backgrounds include upstream interactions of the beam with material, decays of μ, π and K in flight, beam tails below a momentum of 50 GeV/c and energy leaks from either ECAL or HCAL. The full set-up as well as the data selection cuts have been simulated. In order to estimate the systematic uncertainties, backgrounds and search sensitivity, dimuon production was used as a reference process due to its rare occurrence, QED-only nature and similar momentum transfer domain as expected for A'-production. The overall detection efficiency was determined to be about 60% and the systematic uncertainty less than 10%. In the whole statistics of 2.84×10^{11} electrons on target in the 2016-2018 data taking, no signal was observed. The expected background is 0.5 events. Figure 2 shows the 90% C.L. exclusion regions in the ϵ–$m_{A'}$ parameter space (left) and the $y - m_\chi$ parameter space (right) with $y = \epsilon^2 \alpha_D (m_\chi / m_{A'})^4$, α_D denoting the χ-A' coupling constant. Assuming $\alpha_D = 0.1$, NA64 is thus the first beam-dump experiment to have touched the Elastic and Inelastic Scalar Relic sensitivity. Further details on the experiment and analysis can be found in Ref. [6].

3. Searches for the Visible Decay $A' \to \mathrm{e^+e^-}$ and X(17)$\to \mathrm{e^+e^-}$

Figure 3 depicts the set-up for searches with $\mathrm{e^+e^-}$ final states, mainly keeping the original set-up as described in the last section, but with the important addition of a short tungsten calorimeter (WCAL) as the active target. The new calorimeter has been designed to optimise the sensitivity for short A' and X lifetimes, which was also the argument for increasing the electron beam momentum to 150 GeV/c. New veto counters have been added as well and a vacuum pipe between WCAL and ECAL. The experimental signature is a balanced energy between the sum of WCAL and ECAL compared to the energy of the incoming beam and no signal in vetos and HCAL. Both WCAL and ECAL shall contain furthermore only one shower each. Although the electron beam in H4 has a good purity, the remaining fraction of 1% pions and 0.2% kaons lead

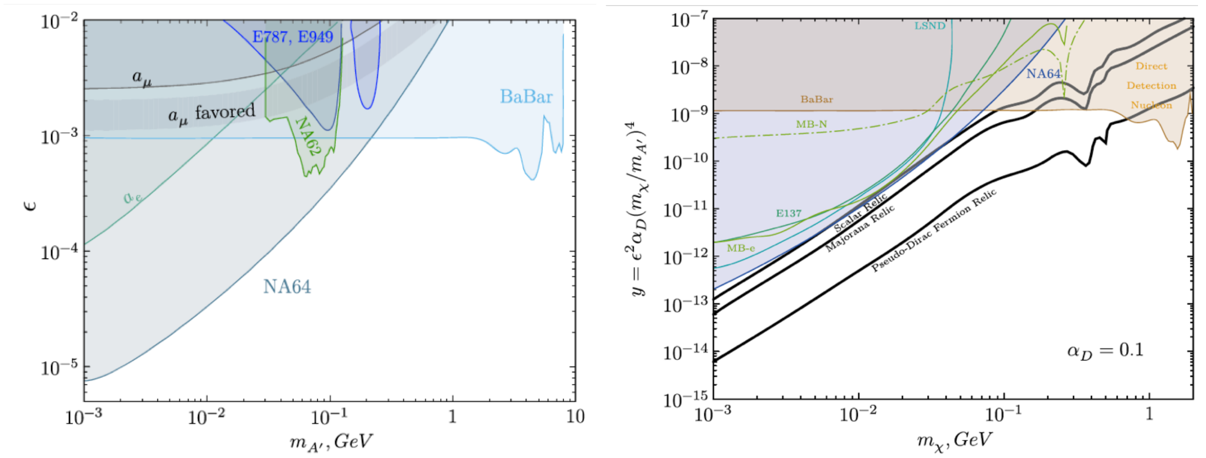

Figure 2. Left: The NA64 90% C.L. exclusion region in ϵ–$m_{A'}$ parameter space, taken from Ref. [6], together with the favoured area of α_μ. Constraints from the E787 and E949 [7, 8], BABAR [9], and NA62 [10] are depicted, as well. Right: The NA64 90% C.L. exclusion region in $y - m_\chi$ parameter space, taken from Ref. [6] and references therein.

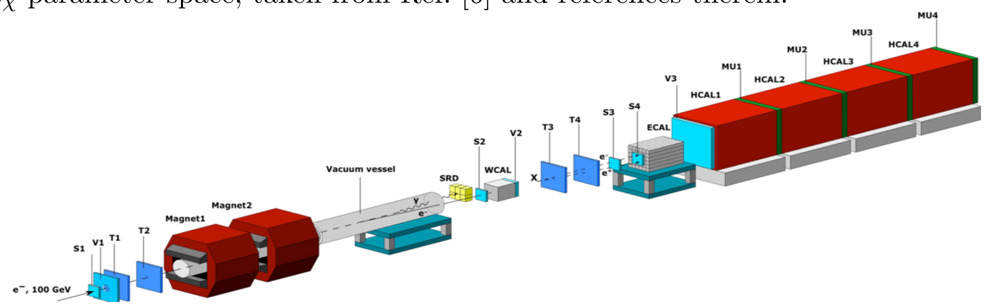

Figure 3. NA64 set-up for visible decay searches.

to the main source of background, i.e. $K_S^0 \to \pi\pi$ decays produced from a mistagged hadron in the beam. In the 2017 data set, three events in the signal region could be identified as photons, which lead to a further upgrade of the set-up for the 2018 data taking. In the combined data set of 8×10^{10} EOT, no signal has been observed with an expected background for 2017 of 0.07 events and 0.006 events for 2018. The 90% C.L. exclusion region in ϵ–$m_{A'}$ parameter space is presented in Fig. 4. The red line is the corresponding parameter space for a hypothetical X(17) boson, which could explain the ATOMKI anomaly and is largely excluded by NA64. Further details on the experiment and analysis can be found in Refs [11, 12, 13].

4. Future searches with muon beams – NA64μ

Besides extending the accessible mass range for dark matter searches toward higher masses, muon beams can be used also for searches for light gauge bosons that hypothetically couple predominantly to muons and/or taus. Such bosons could be either scalar (S_μ) or vector (Z_μ) mediators and provide a possible explanation[14] for the long-standing 3.6σ discrepancy between the measured and theoretically calculated values of the anomalous magnetic moment of the muon, especially as an explanation via a dark photon A' could be already ruled out in the invisible decay channel by combined data from NA64, BABAR[9], and NA62[10]. A possible implementation in the M2 beam at CERN as proposed [15] by NA64 could be along the lines of the set-up for visible modes, accompanied by additional veto counters and another spectrometer stage to cross-check the incoming muon momentum as low-energy tails naturally occur in muon beams. A detailed simulation of beam properties and a proposal for integration of the experiment in the existing beamline with minimum changes has been done recently by the PBC Conventional Beams working group, details can be found Refs [16, 17, 18].

5. Conclusions and Outlook

Active beam-dump searches for light dark matter have been proven by the NA64 experiment to be very powerful via both invisible and visible modes, now for the first time touching scalar relic sensitivity. The future combined search with both electron and muon beams has a good potential to probe a large area of the light dark matter parameter space, especially towards higher masses. While data taking with electron beams is already approved to continue in 2021 with an improved set-up [19], the muon beam proposal [15] is currently under consideration by the SPSC committee. Detailed studies have been provided by the "Physics Beyond Colliders" Conventional Beams working group and a pilot run for tests in the M2 beamline is currently being prepared. In addition, further searches for invisible decays of hadrons and for milli-charged particles are being investigated by the collaboration at the moment.

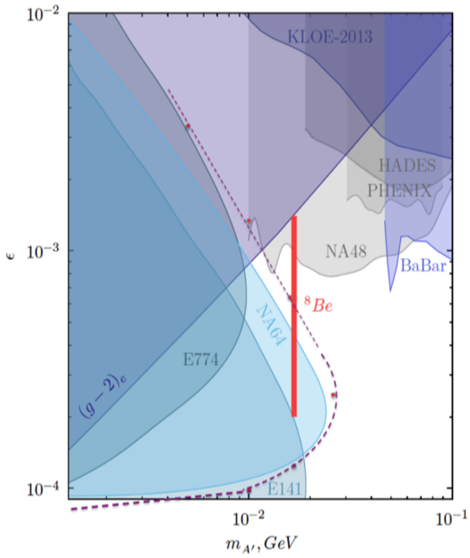

Figure 4. The NA64 90% C.L. exclusion region in ϵ–$m_{A'}$ parameter space with the combined 2017 (light blue) and preliminary 2018 (dashed line) data set. The red line is the corresponding parameter space for a hypothetical X(17) boson, which could explain the ATOMKI anomaly [4].

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