Addendum to the NA64 Proposal: Search for the $A' \rightarrow invisible$ and $X \rightarrow e^+e^-$ decays in 2021

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ABSTRACT:

The experiment NA64 is aimed at a direct search for sub-GeV vector mediator A' of Dark Matter production in invisible A' decay mode. Another goal is to search for of a new light X boson, which could explain a recently observed excess of e^+e^- events from excited ^{8}Be transitions. The NA64 Collaboration requests to carry out further both searches with the H4 electron beam in the year 2021 and beyond.

Contents

SUMMARY

The recently performed measurements in 2016-17 are a part of a broad NA64 program which address the most important issues currently accessible to the dark sector:

  (i) a search for the $A' \to invisible$ decay of the dark photons which could mediate light thermal Dark Matter production, and

  (ii) the search for the $X \to e^+e^-$ decay of a new light boson X which may explain the ^{8}Be anomaly - an excess of e^+e^- events in the excited ^{8}Be transitions.

The upcoming run in 2018, combined with the 2016-17 NA64 runs, provides us with the opportunity to meet and perhaps exceed our original goals for both programs and to start on a new physics program for the future.

During the 2016-17 runs, we collected $\simeq 10^{11}$ electron on target (EOT). About 6 months of running time after the LS2 in 2021-23 will allow us to increase significantly the 2016-18 data sample and improve sensitivity to the mixing strength by a factor ten. Our goals for the 2021-23 runs are:

  (i) to increase the statistics in the invisible A' decay by an order of magnitude up to a few 10^{12} EOT in order to probe theoretically motivated region ($10^{-6} \lesssim \epsilon \lesssim 10^{-3}; m_{A'} \lesssim 1$ GeV) in the ($\epsilon; m_{A'}$) parameter space.

  (ii) to continue searches for scaler, Majorana, and Pseudo-Dirac light thermal Dark Matter, and to set stringent constraints on the dark coupling and masses in the ($\alpha_D; m_{A'}$) plane

  (iii) to complete the search for the $X \to e^+e^-$ decay of a new gauge boson which could explain the ^{8}Be anomaly.

1 Introduction

Despite the intensive searches at the LHC and in non-accelerator experiments Dark Matter (DM) still is a great puzzle. Though stringent constraints obtained on DM coupling to standard model (SM) particles ruled out many DM models, little is known about the origin and dynamics of the dark sector itself. One difficulty so far is that DM can be probed only through its gravitational interaction. An exciting possibility is that in addition to gravity, a new force between the dark sector and visible matter transmitted by a new vector boson A' (dark photon) might exist. Such A' could have a mass $m_{A'} \lesssim 1$ GeV - associated with a spontaneously broken gauged $U(1)_D$ symmetry- and couple to the SM through kinetic mixing with the ordinary photon, $-\frac{1}{2}\epsilon F_{\mu\nu} A'^{\mu\nu}$, parametrized by the mixing strength $\epsilon \ll 1$. This has motivated a worldwide theoretical and experimental effort towards searches for dark forces and other portals between the visible and dark sectors, shifting the strategy from the high energy to the high intensity frontier, see Refs. [1, 2] for a review.

An additional motivation for existence of the A' has been provided by hints on astrophysical signals of dark matter [3], as well as the 3.6 σ deviation from the SM prediction of the muon anomalous magnetic moment $g_\mu - 2$, which can be explained by a sub-GeV A' with the coupling $\epsilon \simeq 10^{-3}$. Such small values of ϵ could naturally be obtained from loop effects of particles charged under both the dark and SM $U(1)$ interactions with a typical 1-loop value $\epsilon = eg_D/16\pi^2$ [4], where g_D is the coupling constant of the $U(1)_D$ gauge interactions. A dark photon mass in the sub-GeV range, $m_{A'} \simeq \sqrt{\epsilon} M_Z$, can be generated in several physics scenarios. Thus, if $U(1)_D$ is embedded in a Grand Unifed Theory (GUT), the mixing can be generated by a one-(two-)loop interaction and naturally results in values of $\epsilon \simeq 10^{-3} - 10^{-1}(10^{-5} - 10^{-3})$ [3–5].

If the A' is the lightest state in the dark sector, then it would decay mainly visibly, i.e., typically to SM leptons $l = e, \mu$ or hadrons, which could be used to detect it. Previous beam dump, fixed target, collider, and rare meson decay experiments have already put stringent constraints on the mass $m_{A'}$ and ϵ of such dark photons excluding, in particular, the parameter region favored by the $g_\mu - 2$ anomaly [2]. However, in the presence of light dark states, in particular dark matter, with the masses $< m_{A'}$, the A' would predominantly decay invisibly into those particles provided that $g_D > \epsilon e$. Models introducing such invisible A' offer new intriguing possibilities to explain the $g_\mu - 2$ and various other anomalies and are subject to different experimental constraints. Compared to the visible decay mode, the invisible decay is constrained in significantly smaller $(\epsilon; m_{A'})$ parameter space living large area still unexplored.

The NA64 was designed as a hermetic general purpose detector to search for dark sector physics in missing energy events from electron, hadron, and muon scattering off nuclei. Because of the higher energy of the incident beam, the centre-of-mass

system is boosted relative to the laboratory system. Taking this boost into account results in enhanced hermeticity of the detector providing a nearly full solid angle coverage. This NA64 report to the SPSC focuses mostly on the status of the analysis of data accumulated during runs in 2016-17. The results from these first sets of measurements in were taken into account also for the detector preparation for the run 2018 which is currently underway as planned. The detector has been completely commissioned.

For the success of NA64 the precise identification of the initial state, i.e. the knowledge of the incoming particle ID and its momentum is crucial. The important milestone in development of such tagging system in 2016 was the development and running of the complete Synchrotron Radiation Detector(SRD) consisting of three fully functioning modules. Another important step was the deployment of the completely commissioned Micromegas and GEM chamber tracker. In 2016 data taking was performed at three different intensities. The results from the high intensity run data analysis are as expected confirming that the NA64 is be able to run at high intensities up to $\simeq 5 \times 10^6$ e$^-$ / spill. We should underline that at this stage of the experiment in order to probe the previously discussed $(\epsilon, m_{A'})$ parameter space, accumulating of 10^{12} or more eot and good data quality and efficiency required taking data at the ultimate sustainable rate of $\gtrsim 5 \times 10^6$ e$^-$ / spill. This is especially true because the analysis is sensitive to the pileup level which depends on the instantaneous beam rate.

The document is organized as follows. Sec.2 provides an overview of the NA64 method of search, the summary of the data collected in 2016/17, and the detector performance. Sections present the proposal for the continuation of the ongoing program in 2021 and beyond. It includes plans for 2017/18 and beyond the LS2, as well as the the results on feasibility study of the search for the $X \to e^+e^-$ decay of a new light boson X which could explain the ^{8}Be anomaly. Detector upgrade and request for its permanent location at the H4 line are presented in Sec. 4, while the Conclusion is given in Sect. 5, respectively.
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2 Status of the 2016/17 NA64 runs

The NA64 experiment ran six weeks with the H4 electron beam in 2016, and about five week by the end of 2017. The full review of the status and results obtained by NA64 in 2016 can be found in Ref. [6]. In the following we briefly summarize the performance of the detector during these runs, and give the current status of data analysis for NA64.

The method of the search is as follows [7–9]. If the A' exists it could be produced via the kinetic mixing with bremsstrahlung photons in the reaction of high-energy electrons scattering off nuclei of an active target of a hermetic detector, followed by
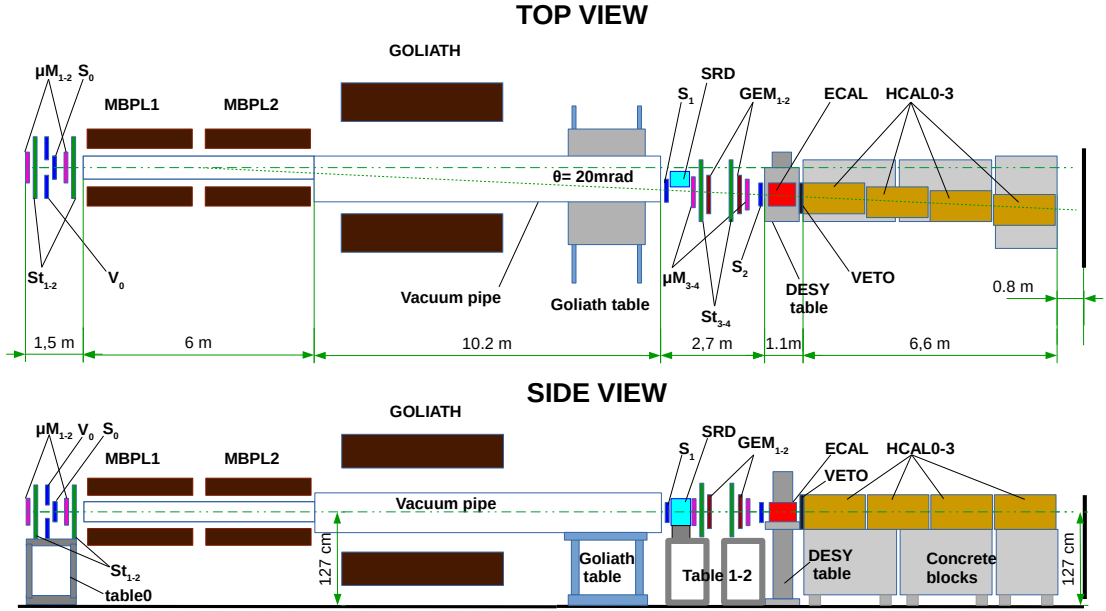
Figure 1. Schematic illustration of the setup to search for $A' \to invisible$ decays of the bremsstrahlung A's produced in the reaction $eZ \to eZA'$ of 100 GeV e$^-$ incident on the active ECAL target.

the prompt $A' \to invisible$ decay into dark matter particles (χ):

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

A fraction f of the primary beam energy $E_{A'} = f E_0$ is carried away by χ's which penetrate the detector without interactions resulting in an event with zero-energy deposition. While the remaining part $E_e = (1 - f)E_0$ is deposited in the target by the scattered electron. Thus, the occurrence of A' produced in the reaction (2.1) would appear as an excess of events whose signature is a single electromagnetic (e-m) shower in the target with energy E_e accompanied by a significant missing energy $E_{miss} = E_{A'} = E_0 - E_e$ above those expected from backgrounds. Here we assume that the χs have to traverse the detector without decaying visibly in order to give a missing energy signature. No other assumptions on the nature of the $A' \to invisible$ decay are made.

The NA64 detector is schematically shown in Fig. 1. The experiment employed the optimized 100 GeV electron beam from the H4 beam line. The beam has a maximal intensity $\simeq 5 - 7 \times 10^6$ per SPS spill of 4.8 s produced by the primary 400 GeV proton beam with an intensity of a few 10^{12} protons on target. The detector

utilized the beam defining scintillator (Sc) counters S1-S3 and veto V1, and magnetic spectrometer consisting of two successive dipole magnets with the integral magnetic field of $\simeq 7$ T·m and a low-material-budget tracker. The tracker was a set of two upstream Micromegas chambers (T1, T2) and two downstream sets of (MM+GEM) stations (T3, T4) allowing the measurements of the e^- momentun with the precision $\delta p/p \simeq 1\%$ [10]. The magnets also served as an effective filter rejecting low energy component of the beam. To enhance the electron identification the synchrotron radiation (SR) emitted by electrons was used for their efficient tagging. A 15 m long vacuum vessel between the magnets and the ECAL was installed to minimize absorption of the SR photons detected immediately at the downstream end of the vessel with a SR detector (SRD), which was either an array of $B_4Ge_3O_{12}$(BGO) crystals or a PbSc sandwich calorimeter of a very fine segmentation [11]. By using the SRD the initial level of the hadron contamination in the beam $\pi/e^- \lesssim 10^{-2}$ was further suppressed by a factor $\simeq 10^3$. The detector was also equipped with an active target, which is an electromagnetic calorimeter (ECAL) for measurement of the electron energy deposition E_{ECAL} with the accuracy $\delta E_{ECAL}/E_{ECAL} \simeq 0.1/\sqrt{E_{ECAL}}$. The ECAL was a matrix of 6×6 Shashlik-type modules assembled from Pb and Sc plates with wave length shifting fiber read-out. Each module was $\simeq 40$ radiation lengths. Downstream the ECAL the detector was equipped with a high-efficiency veto counter V2, and a massive, hermetic hadronic calorimeter (HCAL) of $\simeq 30$ nuclear interaction lengths. The HCAL served as an efficient veto to detect muons or hadronic secondaries produced in the e^-A interactions in the target. The HCAL energy resolution was $\delta E_{HCAL}/E_{HCAL} \simeq 0.6/\sqrt{E_{HCAL}}$. Four muon plane counters, MU1-MU4, located between the HCAL modules were used for the muon identification in the final state. The occurrence of A' produced in the reaction (2.1) would appear as an excess of events whose signature is a single electromagnetic (e-m) shower in the target with energy E_e accompanied by a significant missing energy $E_{miss} = E_{A'} = E_0 - E_e$ above those expected from backgrounds. Here we assume that the χs have to traverse the detector without decaying visibly in order to give a missing energy signature. No other assumptions on the nature of the $A' \to invisible$ decay are made. The signal candidate events have the signature:

$$S_{A'} = \Pi S_i \times PS \times ECAL \times \overline{Veto} \times \overline{HCAL}, \tag{2.2}$$

and should satisfy the following selection criteria:

- The starting point of the shower should be localized within few first X_0 in PS.

- The fraction of the total energy deposition in the ECAL is $f \lesssim 0.8$. The lateral and longitudinal shapes of both showers in ECAL are consistent with an electromagnetic one.

- No energy deposition in the Veto.

- No activity in the HCAL.

2.1 The SPS H4 secondary beam line

The experiment uses the optimized CERN SPS H4 e^- beam, which is produced in the target T2 of the CERN SPS and transported to the detector in an evacuated beam-line tuned to a freely ajustable beam momentum from 10 up to 300 GeV/c. The typical maximal beam intensity at $\simeq 100$ GeV, is of the order of 5×10^6 e^- for one typical SPS spill with a few 10^{12} protons on target. Note, that a typical SPS cycle for Fixed Target (FT) operation lasts 14.8 s, including 4.8 s spill duration. The number of FT cycles is typically 2 per minute.

To provide as maximal as possible coverage of still unexplored area of the $\gamma - A'$ mixing strength $10^{-6} \lesssim \epsilon_e \lesssim 10^{-3}$ and masses $m_{A'} \simeq 1$ GeV one needs to accumulate $n_{eot} \gtrsim 10^{12}$ EOT. Reaching this goal would require i) an average 100 GeV e^- H4 beam intensity of $\gtrsim 5 \times 10^6$ e^- per SPS spill; and ii) the data-taking period of $\simeq 6$ months, assuming on average $\simeq 4 \times 10^3$ SPS spills/day and 50% overall efficiency. Since so far we do not have special requirements for the beam size at the entrance to the detector, which can be within a few cm^2, the beam intensity can be increased by a factor up to 1.5 by tuning the beam line optics and collimators up to $\simeq (7-8) \times 10^6$ e^- per SPS spill. It is assumed that the contamination of particles, others than electrons will still be at the level $\lesssim 10^{-2}$.

A two-stage approach is envisaged for the experiment, incorporating initial experimental phase in 2016-2018, followed by the main-goal period of the experiment to reach the planned sensitivity in 2021-2023.

2.2 Data sample and preliminary results from September 2017 run

The September 2017 run was divided into two data-taking periods, of which the first one used for the $A' \rightarrow invisible$ running and the second one for the search for the rare decay $X \rightarrow e^+ e^-$. The first period was subdivided into several runs with gradually increased intensity of the electron beam in order to study of the search for the $A' \rightarrow invisible$ decay at maximal beam intensity. For these runs,

(i) The detector option with two magnets shown in Fig.1 was used for the primary electron identification with the PbSc SRD detector having the transverse segmentation.

(ii) The following data samples:

- $n_{eot} \simeq 2.0 \cdot 10^{10}$ eot with intensity $\simeq 3 - 4 \cdot 10^6$ e$^-$/spill
- $n_{eot} \simeq 2.2 \cdot 10^{10}$ eot with intensity $\simeq 4 - 5 \cdot 10^6$ e$^-$/spill
- $n_{eot} \simeq 1.0 \cdot 10^{10}$ eot with intensity $\simeq 5 - 8 \cdot 10^6$ e$^-$/spill

were recorded (the numbers of EOT are still preliminary).

(iii) Two upstream MM1 and MM2 were use to reject large angle tracks and improve collinearity of the incoming beam. Two downstream MM3 and MM4 , as well as GEM1 and GEM 2 station were used for the track finding and its momentum definition.

(iv) To increase the operational efficiency of the experiment the upgraded DAQ system, improved Data Quality Control system were used in the run.

(v) Currently, the development of improved version of the reconstruction and analysis program for the September 2017 data sample is in progress, as well as the study of systematic effects, background sources for the final detector configuration in 2017. Preliminary results looks promising.

The primary events were collected with the hardware trigger of (2.2) requiring an in-time cluster in the ECAL with the energy $E_{ECAL} \lesssim 80$ GeV. The candidate events were selected with the criteria chosen to maximize the acceptance for MC signal events and to minimize the numbers of background events, respectively, which are similar to the criteria used for the analysis of the data from July run. The following quite moderate selection criteria were applied: (i) The incoming particle track should have a small angle with respect to the beam axis to reject large angle tracks from the upstream e^- interactions. No cuts on reconstructed momentum were used. (ii) The energy deposited in three SRD detectors should be within the SR range emitted by e^-s and in-time with the trigger. This was the key cut identifying the pure initial e^- state. (iii) The lateral and longitudinal shape of the shower in the ECAL should be consistent with the one expected for the signal shower [12]. (iv) There should be no activity in V2. The the signal box corresponds to the region $E_{ECAL} < 0.5E_0; E_{HCAL} < 1$ GeV.

For the data from September run significant effort has gone into studying performance of the detector at high beam rate $\simeq 5 - 8 \cdot 10^6$ e$^-$/spill. Currently the analysis is in progress. Additional studies have been devoted to the further improvement of the efficiency loss caused by the pileup effect which is slightly different for all used sub-detectors, and if not taken into account, would result in a overall efficiency drop in the $A' \to invisible$ search. We still continue working on the pileup removal algorithm and the tracker efficiency. This work in progress.

Similar to the 2016 run, the selection criteria and requirements for the September data were chosen to optimize acceptance for signal events and the sensitivity and signal to background ratio. The preliminary results reported here came mostly from a set of data in which $n_{EOT} \simeq 10^{10}$ of eot were collected with the beam intensity $\simeq (3 - 4) \times 10^6$ e$^-$ per spill. A smaller sample of $n_{EOT} \simeq 5 \times 10^9$ and an intensity $I_e \simeq 5 - 8 \times 10^6$ e$^-$ was also analysed. Data of these two runs were analyzed with similar selection criteria. The signal box corresponds to the region $E_{ECAL} < 0.5E_0; E_{HCAL} < 1$ GeV.
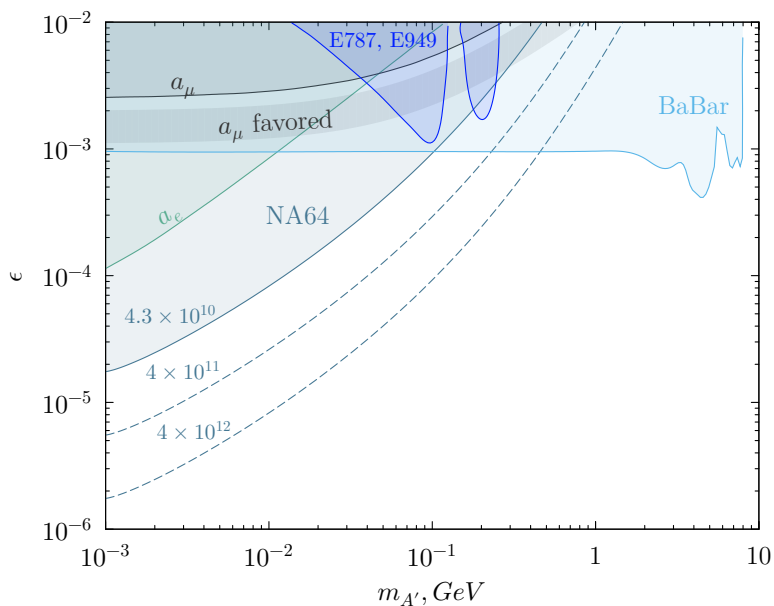
Figure 2. The expected NA64 90% C.L. exclusion region in the $(m_{A'}, \epsilon)$ plane for the different number of EOT. The bound from the experiments E787, E949 [16], and BaBar [17] experiments are also shown.

3 Continuation of the ongoing program in 2021 and beyond

Successful runs in 2017 and beyond, after LS2, will be an important step in the continuing dark sector physics program at CERN. The combined 2016-2023 runs will allow us to accumulate more than 10^{12} EOT and complete our search of the $A' \rightarrow invisible$ decays and to reach our proposed sensitivities for the theoretically motivated region of the $(\epsilon; m_{A'})$ parameter space and a wide set of rare processes. It can also play an essential role in helping us plan for a future dark sector experiments at the SPS, e.g. with a muon beam. With detector upgrades over time and the availability of significantly higher electron, muon and hadronic fluxes at the SPS, it should eventually be possible to detect and measure many other important rare processes and decay modes as reported at the PBC kick-off workshop and BSM working group meetings.

3.1 Search for the $A' \rightarrow invisible$ decays

The successful run in 2016/17 with two-spill structure during 48 sec cycle time and intensity $\gtrsim 5 \times 10^6$ EOT/spill gave us a significant increase in the A' yield. An extrapolation from these runs shows that we can collect $\gtrsim 3 - 4 \times 10^{12}$ EOT in $\simeq$ 6 months of running. The combined 2016-18 and 2021-23 data sample will include more than 3×10^{12} EOT resulting in a significant coverage of the $(\epsilon; m_{A'})$ parameter space up to $\epsilon \lesssim 10^6; m_{A'} \lesssim 1$ GeV and $\alpha_D \lesssim 1, m_{DM} \lesssim 1$ GeV.

3.1.1 Sensitivity evaluation for the mixing strength

The $m_{A'}$-dependent upper limit on the mixing ϵ is calculated as follows. For a given number n_{EOT} and the mass $m_{A'}$, the number of signal events $N_{A'}$ expected from the reaction (2.1) in the signal box is given by:

$$N_{A'} = n_{EOT} \times n_{A'}(\epsilon, m_{A'}, \Delta E_{A'}) \times \epsilon_{A'}(m_{A'}, \Delta E_{A'}) \tag{3.1}$$

where $n_{A'}(\epsilon, m_{A'}, \Delta E_{A'})$ is the yield of A's with the coupling ϵ, mass $m_{A'}$, and energy in the range $\Delta E_{A'}$, $0.5E_0 < E_{A'} < E_0$, per e-m shower generated by a single 100 GeV electron in the ECAL [12]. These events correspond to the missing energy $0.5E_0 < E_{miss} < E_0$. The overall signal efficiency, $\epsilon_{A'}$ is slightly $m_{A'}, E_{A'}$ dependent and is given by the product of efficiencies accounting for the NA64 geometrical acceptance (0.97), the analysis efficiency ($\simeq 0.8$), veto V2 (0.96) and HCAL signal efficiency (0.94) and the acceptance loss due to pileup $\simeq 7\%$ for PbSc run [13]. For the number of collected $n_{EOT} \gtrsim 4 \times 10^{10}$ eot was obtained from the recorded number of reference events from the e-m e^-Z interactions in the target by taking into account the trigger suppression factor ($\gtrsim 10^2$) and dead time (0.93). The e^- beam loss due to interactions with the beam line materials was found to be small. The trigger (SRD) efficiency obtained by using unbiased random samples of events that bypass selection criteria was found to be 0.95 (0.97) with a small uncertainty 2% (2%). The A' acceptance was evaluated by taking into account the selection efficiency for the lateral and longitudinal shape of e-m showers in the ECAL from signal events [12]. The A' yield is calculated as described in Ref.[12]. To estimate additional uncertainty in the A' yield prediction, the cross-check between a clean sample of observed and MC predicted $\mu^+\mu^-$ events with $E_{ECAL} \lesssim 60$ GeV was made, resulting in additional $\simeq 10\%$ uncertainty in the dimuon yield. The overall signal efficiency $\epsilon_{A'}$ varied from 0.69 ± 0.09 to 0.55 ± 0.07 decreasing for the higher A' masses.

In accordance with the CL_s method, for zero observed events the 90% C.L. upper limit for the number of signal events is $N_{A'}^{90\%}(m_{A'}) = 2.3$. Taking this and Eq.(3.1) into account and using the relation $N_{A'}(m_{A'}) < N_{A'}^{90\%}(m_{A'})$ [14, 15] results in the 90% C.L. exclusion area in the $(m_{A'}; \epsilon)$ plane shown in Fig. 2 for different total number of accumulated EOT. The further improvement in sensitivity on ϵ for the background-free case scales as $1/\sqrt{n_{EOT}}$. Moreover, the results obtained allow us to restrict other models with light scalars interacting with electrons and decaying predominantly to invisible modes.

3.1.2 Constraints on light thermal Dark Matter

Models with light dark matter ($m_{DM} \leq 1\ GeV$) can be classified by the spins and masses of the dark matter particles and mediator. The scalar dark matter mediator models are severely restricted or even excluded by nonobservation of rare B-meson decays so we consider here only the case of vector mediator [18]. The most popular

vector mediator model is the model with additional massive photon $A^`$ which couples with dark matter particles via interaction $L_I = g_D A^`_\mu J^\mu_D$ with coupling constant $g_D (\alpha_D \equiv \frac{g^2_D}{4\pi})$[1]. The mixing $L_{mix} = -\frac{1}{2}\epsilon F^{\nu\nu} F^`_{\mu\nu}$ between photon field A_μ and dark
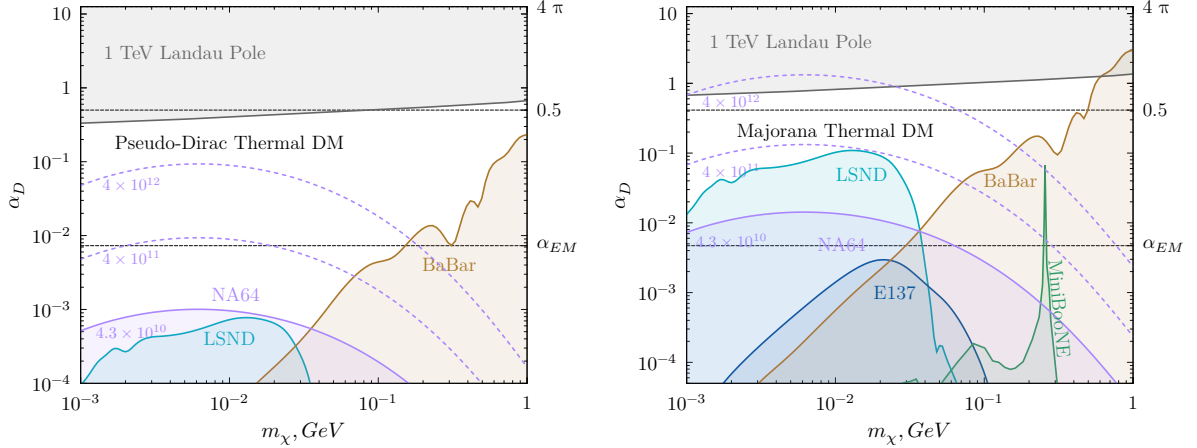

Figure 3. Constraints in the $(\alpha_D; m_{A'})$ plane on the Pseudo-Dirac (the left panel) and Majorana (right panel) type light thermal Dark Matter (reproduced from [19]). The NA64 curves represent the constraints obtained form the 2016 (magenta solid) [13], and projected combined limit from the 2021-23 (magenta dashed) runs [20].

photon field $A^`_\mu$ leads to nonzero interaction of dark photon $A^`_\mu$ with the electrically charges SM particles with the charges $e^` = \epsilon e_{SM}$. So as a result of mixing the annihilation cross-section of DM particles is proportional to $\epsilon^2$. The dark matter annihilation cross-section into SM particles determines the dark matter density. Consider at first the case of scalar dark matter. For $m_{A^`} \geq m_\phi$ the rate of annihilation $\phi\phi^* \to f\bar{f}$ determines the relic density [2]. For $m_e \leq m_\phi \leq m_\mu$ the main annihilation channel is into electron-positron pair $\phi\phi^* \to e^-\bar{e}^+$ determines the relic density. Neglecting the m_f mass, the tree level cross section at relative velocity $v_{rel} \ll c$ is

$$\sigma v_{rel} = \frac{8\pi}{3} \frac{\epsilon^2 \alpha \alpha_D m^2_\phi v^2_{rel}}{(m^2_{A^`} - 4m^2_\phi)^2 + m^2_A \Gamma^2} , \qquad (3.2)$$

where Γ is the $A^`$ width. In the limit $m_{A^`} \gg m_\phi, \Gamma$, this cross-section depends on dark-sector parameters only through the dark matteer mass m_ϕ and the dimensionless variable

$$y \equiv \epsilon^2 \alpha_D (\frac{m_\phi}{m_{A^`}})^4 , \qquad (3.3)$$

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[1]The currents $J^\mu_{DM} = \bar{\psi}_{DM}\gamma^\mu\psi_{DM}$ and $J^\mu_{DM} = i(\phi^+_{DM}\partial^\mu\phi_{DM} - \phi_{DM}\partial^\mu\phi^+_{DM})$ for spin 1/2 and 0.

[2]Here f is the SM particle.

For fermion dark matter ϕ with vector interaction $L_I = e_D \bar{\phi} \gamma^\mu \phi A'_\mu$ the dark matter annihilation cross section is

$$\sigma v_{rel} = 8\pi \frac{\epsilon^2 \alpha \alpha_D m_\phi^2}{(m_{A'}^2 - 4m_\phi^2)^2 + m_A^2 \, \Gamma^2} .$$

(3.4)

Note that the absence of v_{rel}^2 factor in (3) is due to the fact that the annihilation of fermions takes place in the s-wave. Numerically for $v_{rel} \sim 1/3$ the annihilation cross-section for scalar dark matter is suppressed by factor ~ 25 in comparison with fermion dark matter(for the same mass and α_D, ϵ). For the axial-vector interaction we have p-wave suppressed annihilation with $\sigma v_{rel} \sim v_{rel}^2$ as for the scalar case. If the global $U'(1)$ symmetry under which the Weyl components $\phi_{1,2}$ of Dirac fermion $\phi = (\phi_1, \phi_2^+)$ have opposite charges is broken(by a Higgs field that gives mass to the A' the interaction $L_{break} = \delta \phi_1 \phi_2$ yeld mass eigenstates $\phi_\pm = \frac{1}{\sqrt{2}}(\phi_1 \pm \phi_2)$ split in mass by δ. This corresponds to the inelastic or pseudo-dirac scenario. Analogously inelastic interaction can also arise in scalar case.

The dark matter annihilations freeze out before the era of recombinations, however residual annihilations can reonize hydrogen and distort the high l-CMB power spectrum. The data on the high l-CMB power spectrum exclude thermal-relic Dirac fermion dark matter, but not other scenarios like scalar dark matter in which p-wave suppression of annihilation at late times leads to more weak bound on the parameter y. Also this bound becomes weak for inelastic dark matter. So scalar dark matter or inelasic fermion dark matter models survive. From the equations (2,3) we can estimate the value of y. Namely, for fermion dark matter we find

$$y = <\sigma v> \cdot \frac{m_\psi^2}{8\pi\alpha} \cdot (1 - \frac{4m_\psi^2}{m_{A'}^2})^2$$

(3.5)

Numerically, for $<\sigma v> = 0.3 \cdot 10^{-8} GeV^{-2}$ we find that

$$y = 1.6 \cdot 10^{-12} (m_\psi/10 \ MeV)^2 \cdot (1 - \frac{4m_\psi^2}{m_{A'}^2})^2$$

(3.6)

For scalar dark matter the corresponding estimate reads

$$y = 0.4 \cdot 10^{-10} (m_\psi/10 \ MeV)^2 \cdot (1 - \frac{4m_\psi^2}{m_{A'}^2})^2$$

(3.7)

Constraints in the $(\alpha_D; m_{A'})$ plane on the Pseudo-Dirac (the left panel) and Majorana (right panel) type light thermal Dark Matter obtained from the 2016 run [13] and expected from the 2021-23 runs [20] are shown in Fig.3 under assumption $m_{A'} = 3m_{DM}$ for different number of the accumulated EOT . Here m_{DM} is the mass of dark matter scalars or fermions.

3.2 Search for a new light X boson from the ^{8}Be excess

The experiment of Krasznahorkay et al. [21] in ATOMKI has reported observation of a 6.8 σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the $^8Be^*$ exited state nuclear transitions to its ground state accompanied by an emission of an e^+e^- via internal pair creation. Feng et al. show that this anomaly can be interpreted as an emission of a new protophobic gauge boson followed by its prompt $X \to e^+e^-$ decay [22, 23] and provide a particle physics explanations of the anomaly consistent with all existing constraints assuming its coupling to electrons is in the range $2 \times 10^{-4} < \epsilon_e < 1.4 \times 10^{-3}$ and mass $M_X = 16.7$ MeV. Their models predict relatively large charged lepton couplings $\epsilon_e \simeq 0.001$ that can also resolve the discrepancy in the muon anomalous magnetic moment. They also contain vectorlike leptons at the weak scale that can be accessible to the near future LHC searches.
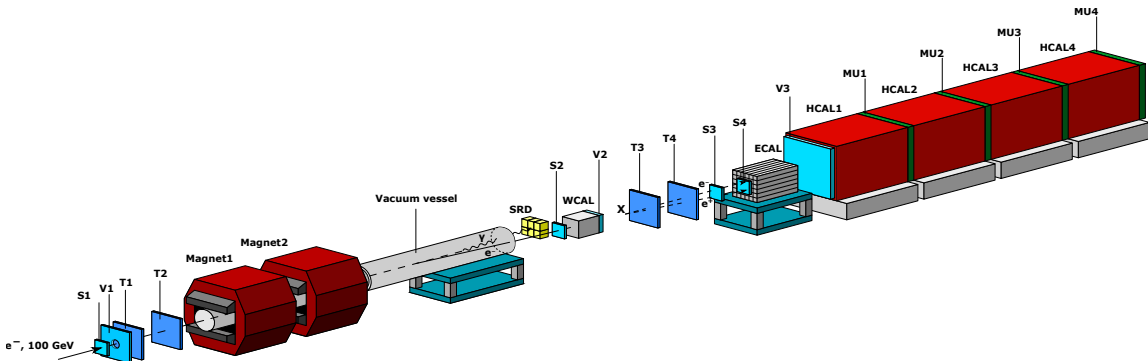

Figure 4. Schematic illustration of the NA64 setup to search for $X \to e^+e^-$ decays with 100 GeV e$^-$ at the H4 beamline.

In October 2016 a short run to test feasibility for the $X \to e^+e^-$ decays search was taken. The detailed discussions of the results from this test can be found in the NA64 report [25]. Briefly, the NA64 detector configuration shown in Fig. 4 employs the 100 GeV e^- beam from the H4 beam line. Upstream of the SRD the detector was identical to that used for the $A' \to invisible$ decay search. Downstream the SRD, the NA64 detector configuration shown in Fig. 4 differed from that used for the $A' \to invisible$ decay search in several respects: the detector was also equipped with an active target, which is an electromagnetic calorimeter (WCAL) used for production of the X in the reaction e$^-Z \to$ e^-ZX and for measurements of the electron energy deposition E_{ECAL} with the accuracy $\delta E_{ECAL}/E_{ECAL} \simeq 0.1/\sqrt{E_{ECAL}}$. The WCAL was a sandwich type calorimeter assembled from W and Sc plates with wave length shifting fiber read-out. It was a single module with $\simeq$ 30 radiation lengths. The tracker was a set of two downstream MM and GEM stations each (T3, T4) allowing to identify the decay e^+e^- pairs.

Downstream the WCAL the detector was equipped with a high-efficiency veto counter V2, the ECAL to measure the energy of decay e^+e^- pair and a massive,

hermetic hadronic calorimeter (HCAL) of $\simeq$ 30 nuclear interaction lengths. The HCAL served as an efficient veto to detect muons or hadronic secondaries produced in the $e^- A$ interactions in the WCAL or ECAL. Four muon counters, MU1-MU4, located between the HCAL modules were used for the muon identification in the final state.

The occurrence of $X \to e^+ e^-$ decays produced through the reaction [7, 8]

$$e^- + Z \to e^- + Z + X; \; X \to e^+ e^- \tag{3.8}$$

of 100 GeV e^- would appear as an excess of events with two e-m-like showers in the detector: one shower in the WCAL, and another one in the ECAL, see Fig. 4, above those expected from the background sources. The signal candidate events have the signature $S_X = \Pi S_i \times \text{WCAL} \times \overline{V2} \times \text{ECAL} \times \overline{V2} \times \overline{V3} \times \overline{\text{HCAL}}$. At sufficiently high X energies $E_X \gtrsim 30$ GeV, the opening angle $\Theta_{e^+ e^-} \simeq M_X / E_X$ of the decay $e^+ e^-$ pair is too small to be resolved in two e-m showers in the ECAL, so the pairs are mostly detected as a single electromagnetic shower. At distances larger than $\simeq$ 5 m from the WCAL, the distance between the hits is $\gtrsim$ 5 mm, so the $e^+ e^-$ pair can be resolved in two separated tracks in the T3 and T4 tracker stations. The total number of $n_{eot} \simeq 5 \cdot 10^9$ eot with intensity $\simeq (2-5) \cdot 10^6$ e- / spill were recorded.

The very preliminary analysis of distribution of the selected candidate events on the in the (E_{WCAL}, E_{ECAL}) plane from the September 2017 run accumulated about 5×10^{10} EOT, shows that after the application of all cuts a few signal candidates events are left in the data in the signal band $E_0 = E_{WCAL} + E_{ECAL}$. Background events analysed with "neutral" trigger are distributed in the low energy part of the plot and most of them were identified as hadronic secondaries from the electroproduction in the WCAL target and a few candidate events left in the $X \to e^+ e^-$ signal region $90 \lesssim E_{tot} \lesssim 110$ GeV. The number of expected background events are currently under study. It was observed that additional strong suppression of backgrounds is possible by using cuts on the two-shower shape expected in the ECAL. These requires more development of the analysis program of the two-shower shape which is in progress. Another contribution to the background is expected either from the high-energy punch-trough photons or from the hadronic interactions with large π^0 component and the little charged hadron activity.

In Table 1 expected contributions from all background sources are summarized for the beam energy of 100 GeV for events accumulated in 2016 run. The dependence on the energy is rather weak. The total background level is conservatively $\lesssim 10^{-10}$, and is dominated by the high-energy γ punch-throughs with a possible contribution from an admixture of hadrons in the electron beam. Thus, a search accumulating up to $\simeq 10^{11} e^-$ events, is expected to be either background free, or with a small background which is well under control. To evaluate the background in the signal region from the punch-through gammas events selected with the neutral trigger, i.e. with requirements of no signal in V2, S2, and S4 counters, are currently under

Table 1. Expected contributions from different background sources estimated for the beam energy 100 GeV (see text for details).

Source of background	Expected level
punchthrough γs	$< 10^{-10}$
hadronic reactions	$\lesssim 2 \times 10^{-13}$
μ reactions	$\lesssim 10^{-14}$
accidentals	$\lesssim 10^{-14}$
Total (conservatively)	$< 10^{-10}$

study. No events are expected to be observed in the signal region corresponding to the condition $E_0 = E_{WCAL} + E_{ECAL}$. This allows to set a 90% C.L. upper limit $P_{pth} < 10^{-9}$/eot on the probability to observed a single punch-through event with energy $E_{pth}^{\gamma} \gtrsim 50$ GeV per eot, which is consistent with the above considerations. The significance of the $A' \to e^+e^-$ decay discovery with the described detector scales as [14, 15]

$$S = 2 \cdot \left(\sqrt{n_X + n_b} - \sqrt{n_b}\right), \tag{3.9}$$

where n_X is the number of observed signal events (or the upper limit of the observed number of events), and n_b is the number of background events.

The expected bound for the search for the $X \to e^+e^-$ and $A' \to e^+e^-$ decays, are shown in the left and right panels of Fig. 5, respectively. For the later, if no excess events are found, the obtained results can be used to impose bounds on the $\gamma - X$ mixing strength as a function of the dark photon mass. Taking Eqs. (3.9) into account and using the relation $n_X(M_X) < n_X^{90\%}(M_X)$, where $n_X^{90\%}(M_X)$ is the 90% C.L. upper limit for the number of signal events from the decays of the X with a given mass M_X one can determine the expected 90% C.L. exclusion area in the $(M_X; \epsilon_e)$ plane from the results of the experiment. For the background free case $(n_X^{90\%}(M_X) = 2.3$ *events)*, the exclusion regions corresponding to accumulated statistics 10^{11} eot at 100 GeV are shown in Fig. 5. One can see, that these exclusion areas are complementary to the ones expected from the planned HPS and DarkLight experiments, which are also shown for comparisonn [22, 23].

4   Detector upgrades and location at the H4 line

Although the first NA64 runs overall were quite successful, several difficulties were encountered which will be addressed for the 2021-23 runs. These items are listed and briefly discussed below in this report.
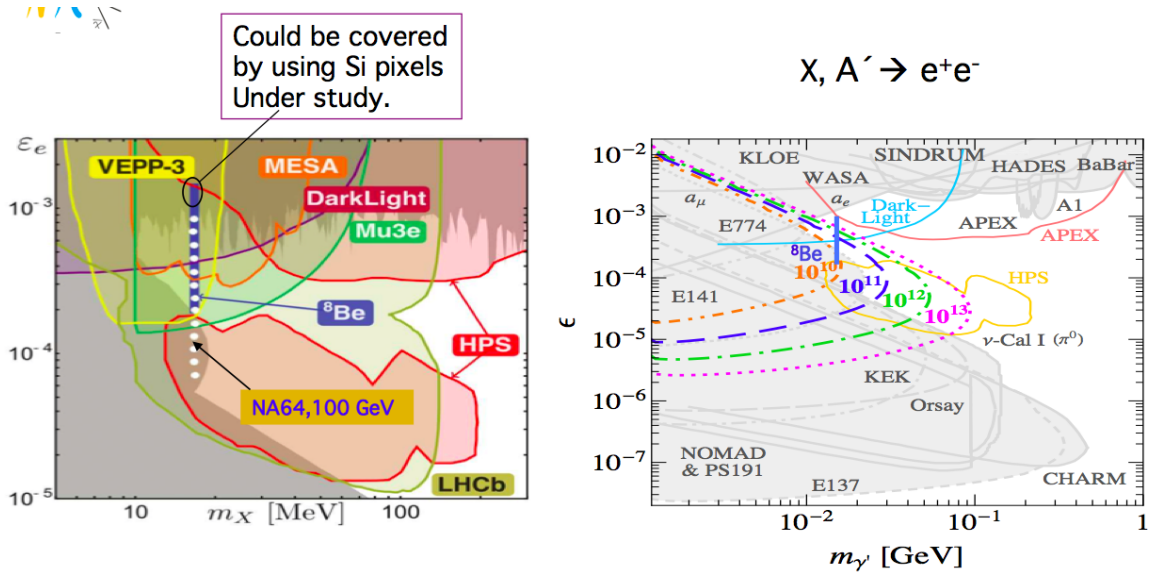
Figure 5. The left panel shows, the ^{8}Be signal region, along with current constraints and projected sensitivities of future experiments in the $(m_x : \epsilon_e)$ plane as discussed in Ref.[22, 23]. The white points indicate expected 90% C.L. exclusion areas in the $(m_X; \epsilon_e)$ plane from NA64 for the accumulated statistics of 10^{11} eot at 100 GeV. For the ^{8}Be signal, the coupling to electrons can be in the range $2 \times 10^{-4} < |\epsilon_e| < 1.4 \times 10^{-3}$, while the excluded area is $7 \times 10^{-5} < |\epsilon_e| < 0.9 \times 10^{-3}$. The remaining part of the ^{8}Be signal parameter space can be covered by using the Si-pixel tracker [20]. The right panel shows expected limits on the $\gamma - A'$ mixing strength obtained from the background free search of the decay $A' \to e^+e^-$ for different number of the accumulated EOT. The exclusion region from other experiments adapted from Ref.[18] are also shown for comparison.

4.1 Detector upgrades for the 2021 run

In the sections below, we describe several detector issues which must be addressed for NA64 to collect data as efficiently as possible in the 2021 run. The upgrades proposed are designed to improve the reliability of the detector and to improve the trigger/DAQ livetime. The improvement in data-taking efficiency will come mainly from the replacement of DAQ components partly described in the NA64 Annual Report 2016. Several modifications to the trigger and front-end readout are required to achieve the live-time improvement. We estimate that the combined improvement will reduce the experiment's overall deadtime (i.e., total beam time for which the experiment is not live) by 10%, equivalent to adding potentially 0.5 weeks per a 4-5 week run.

To increase the overall signal efficiency and improve background rejection the following upgrade of the setup is considered:

(i) additional number of the MM, GEM, ST stations

(ii) pixel detector installed in the magnet for measurements of the invariant mass of e^+e^- pairs from the $X \to e^+e^-$

(iii) two fast beam hodoscopes in the upstream part of the setup

(iv) transversely segmented PbSc SRD detector with improved readout (possibly SiPM)

(v) zero-angle veto to suppress bremsstrahlung photons

(vi) large Veto in front of the ECAL to reject low energy electrons

(vii) upstream small size Sc counter(s) to improve beam divergency. Suppression of background down to the level $\lesssim 1$ event$/10^{11}$ eot seems is feasible.

(viii) Further developments of the DAQ and the analysis program are in progress to ensure a substantial data collection of $n_{eot} \gtrsim$ a few 10^{11} events in 2021.

In September'17 the detector was tested up to $5 \cdot 10^6$ e^-/ spill or $\simeq 10^{10}$ e^-/ collected during one day for the "normal" SPS operation with ~ 2 supercycles per minute. Good performance of the setup was demonstrated. With intensity $\sim 7 \cdot 10^6$ e^-/ spill accumulation $\simeq 10^{11}$ e$^-$ during about 10 days of running is feasible.

4.2 Detector location at the H4 line

As mentioned above, in order to probe the theoretically interesting parameter space $\epsilon \simeq 10^{-5} - 10^{-3}$ and $m_{A'} \lesssim 1$ GeV the number of accumulated electrons on target is required to be around $n_{eot} \gtrsim 3 \times 10^{12}$ or more, and a very low background rate. Assuming the beam rate to be around 5×10^6 e^-/spill around 6 months of data taken are required. Therefore, in order to use more effectively the H4 line, two current drawbacks that we faced for the moment, should be solved:

- Installation of the detector at H4 line from scratch and its debugging takes already about 3 days. Alighment, detector calibration and tuning takes additional 3-4 days more. In 2021-23 more complex setup is expected to be used, resulting in possible increase of time needed for installation, alignment and calibration. As the complexity of the detector increased that time for debugging of the detector is also increased and already reached the level of a few days.

- Tuning of the setup from scratch up to the steadily increased complexity level of the trigger level is also very time consuming procedure. In particular tuning of the SRD detector, beam location, trim scanning due to low threshold,..

Therefore, a permanent location at H4 would be extremely useful to avoid loss of the beam time. We cannot fully take advantage of the H4 beamline until both above issues are solved. If the place for detectors is complete next year, We estimate that the combined improvement will reduce the experiment's overall deadtime (i.e., total beam time for which the experiment is not live) by 30%, equivalent to adding 4.5 weeks to a 20 week run. In total 2 weeks per run could be saved, taken into account weekends and detector calibration.

5 Conclusion

Although NA64's first run was successful and produce significant physics results, we believe we have only begun to exploit the physics potential of the proposed experimental technique and detector. The further runs will provide us with the opportunity to continue this program to meet our original goals for the proposal.

The main goals for the running in 2021-23 are to address several areas of great interest in dark sector physics:

1. to continue the search for the $A' \to invisible$ decay and to reach sensitivity level allowing to probe significant fraction of the theoretically interesting parameter space ($10^{-6} \lesssim \epsilon \lesssim 10^{-3}$; $m_{A'} \lesssim 1$ GeV) and also

2. to continue searches for scalar, Majorana, and Pseudo-Dirac light thermal Dark Matter, and set stringent constraint in the (α_D; $m_{A'}$) plane

3. to complete the search for the $X \to e^+e^-$ decay of a new gauge boson which could explain the ^{8}Be anomaly;

4. continue our studies of $Z_\mu \to invisible$ decay of the $L_\mu - L_\tau$ dark boson, which will include the first prototype detector operating in a realistic muon beam environment.

As discussed in this report, the few issues encountered during the last run are being addressed, so that the 2018 data sample should have better properties than the 2017 data. As the offline analysis proceeds, we also continue to learn how to take better data in 2018 and 2021. Experience gained in the 2017/18 runs will be an important and necessary step towards a program to set a stringent constraints on the dark sector models or, possibly, detect and measure some decay in NA64.

We believe realization of the full potential of NA64 proposed program will require at least 25 weeks of running. It should be noted that this estimate of the running period includes no time for detector assembly for each run, commissioning and tuning, and assumes about 120 hours of a good H4 beam per week. Although physics programs with H4 beam nominally can be realized in a 25 week run, it seems likely that more than 30 calendar weeks, instead of 25, will be required to collect the

data samples described in this report. The allocation of a permanent place for NA64 at H4 would give more running time and provide important contingency against unforeseen losses of the beam time. Additionally, since the year 2018 will be the last for the fixed-target run before the LS2, we believe it is important to collect enough data during 2018 to accumulate as much as possible EOT for the physics goals described above.

We also plan to propose our program of muon and hadron BSM physics which could produced a number of interesting results.

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