The NA64 Collaboration

http://webna64.cern.ch
Abstract:
The experiment NA64 is aimed at a direct search for invisible decays of sub-GeV dark photons ($A'$). The main goal in 2016 was to probe a region of the $A'$ parameter space, particularly interesting for the explanation of the muon $g-2$ anomaly. The status and results from two NA64 runs in July and October 2016, obtained, respectively, with $2.75 \times 10^9$ and $4 \times 10^{10}$ accumulated electron on target are reported. A feasibility study of the search for the $X \rightarrow e^+e^-$ decay of a new light $X$ boson, which could explain a recently observed excess of $e^+e^-$ events from excited $^8\text{Be}$ transitions is also presented.
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The recently performed measurements in 2016 are a part of a broad NA64 program which address the most important issues currently accessible to the dark sector: a search for the $A' \rightarrow \text{invisible}$ decay of the dark photons, in particular in the $A'$ parameter space relevant for the explanation of the muon g-2 anomaly, and a feasibility study of the search for the $X \rightarrow e^+ e^-$ decay of a new light boson $X$ which may explain the $^8\text{Be}$ anomaly - an excess of $e^+ e^-$ events in the excited $^8\text{Be}$ transitions. The upcoming run in 2017, combined with the 2016 NA64 run, 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 runs in July and October, we collected, respectively $2.75 \times 10^9$ and $4 \times 10^{10}$ electron on target (EOT). Five weeks of running time in 2017 will allow us to increase significantly the 2016 data sample and improved sensitivity to the mixing strength by a factor ten. Our goals for the 2017 run are:

(i) to increase the statistics in the invisible $A'$ decay by an order of magnitude;

(ii) to perform the search for a new light $X$ boson with the detector configuration tested in 2016 run and operating in a realistic beam environment at high intensity;

The NA64 collaboration also proposes to carry out further searches of the $A' \rightarrow \text{invisible}$ decay and other rare processes with the H4 electron beam in the years 2018 and after the LS2 with the main goal to accumulate a few $10^{12}$ EOT in order to probe theoretically motivated region in the $(\epsilon; m_{A'})$ parameter space.
1 Introduction

Despite the intensive searches at the LHC and in nonaccelerator 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 $m_{A'} \lesssim 1 \text{ GeV}$ - 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 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 $\sigma$ 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 $\epsilon$ 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 $\epsilon = \frac{g_D e}{16\pi^2}$ [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 Unified 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 $\epsilon$ 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...
was 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 July and October runs in 2016. The results from these first sets of measurements in 2016 were taken into account also for the detector preparation for the run 2017 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 ($\epsilon, m_{\nu}$) 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, and the detector performance. Sec. 3 and 4 present the status of the $A' \rightarrow invisible$ decay and dimuon production analysis, respectively. In Sec. 5 continuation of the ongoing program is described. It includes plans for 2017 and beyond the LS2, as well as the the results on feasibility study of the search for the $X \rightarrow e^+e^-$ 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. 6, while competition, conclusion and finally the status of the NA64 publications are presented in Sect. 7,8,9, respectively.

## 2 Status from the 2016 NA64 run

The NA64 experiment first ran two weeks with the H4 electron beam in July 2016, about four months after the experiment was approved. Following a brief period of commissioning and repairs, the experiment began to collect physics quality data by the end of 2016 during four weeks in October run.

In the following sections, we briefly summarize the performance of the detector during the 2016 run, and give the current status of data analysis for NA64.
The method of the search is as follows \cite{6, 7}. 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 the prompt $A' \rightarrow \text{invisible}$ decay into dark matter particles ($\chi$):

$$e^-Z \rightarrow e^-ZA'; A' \rightarrow \text{invisible}$$ \hspace{1cm} (2.1)

A fraction $f$ of the primary beam energy $E_{A'} = fE_0$ is carried away by $\chi$'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 $E_{\text{miss}} = E_{A'} = E_0 - E_e$ above those expected from backgrounds. Here we assume that the $\chi$s have to traverse the detector without decaying visibly in order to give a missing energy signature. No other assumptions on the nature of the $A' \rightarrow \text{invisible}$ 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 GEM stations (T3, T4) allowing the measurements of \( e^- \) momenta with the precision \( \delta p/p \simeq 1\% \) \[9\]. 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 \( \text{Bi}_2\text{Ge}_3\text{O}_12\) (BGO) crystals or a PbSc sandwich calorimeter of a very fine segmentation \[6\]. 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 \( E_{\text{ECAL}} \) with the accuracy \( \delta E_{\text{ECAL}}/E_{\text{ECAL}} \simeq 0.1/\sqrt{E_{\text{ECAL}}} \). 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 \( \delta E_{\text{HCAL}}/E_{\text{HCAL}} \simeq 0.6/\sqrt{E_{\text{HCAL}}} \). Four muon plane counters, MU1-MU4, located between the HCAL modules were used for the muon identification in the final state.

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 adjustable beam momentum from 10 up to 300 GeV/c. The typical maximal beam intensity at \( \simeq 100 \) GeV, is of the order of \( 5 \times 10^6 \) \( e^- \) 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 assumed to be 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 have to accumulate \( n_{\text{eot}} \gtrsim 10^{12} \) 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
\(\approx 6\) months, assuming on average \(\approx 4 \times 10^3\) SPS spills/day and 50\% the 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 \(\approx (7 - 8) \times 10^6\) e\(^-\) per SPS spill. It is assumed that the contamination of particles, others than electrons still will 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 planned sensitivity in 2021-2024.

### 2.2 Two Magnet option

As test 2015 run results suggest, the second MBPL magnet (2m long, \(\sim 1.8\) T) would be very useful for better e\(^-\) ID at H4. If we use two magnets of 2 m each with a field strength of 1.8 T instead of just one then the separation between the main beam axis and the deflected beam is larger, \(\sim 34\) cm as opposed to 16 cm with one magnet, which helps to suppress the bremsstrahlung photon contribution in the SRD which affects the efficiency of the detector. The new geometry for the beam time in July was as shown in Figure:1 with two MMs (MM1 and MM2) placed before the two magnets and two MMs (MM3 and MM4) placed right before the ECAL with a separation \(\sim 1\) m between them thus minimizing material in the magnet that could create low energy tails like the 50 GeV peak detected in the data. The vacuum between MM2 and MM3 will reduce interactions of primary electrons. The bremsstrahlung photons are produced due to interaction of the primary electron with materials such as the beam windows and MMs placed upstream of the ECAL. There can also be bremsstrahlung contamination in the beam which was noticed from the 2015 data sample. Figure:2 shows the spot of the bremsstrahlung photons at a distance \(\sim 13\) m from the magnets centered at X=0 along the primary beam axis due to interactions before the magnet and deflected by \(\sim 34\) cm due to the interactions downstream of the magnet. Figure:2 shows the spot of the primary electrons on MM4 before the ECAL. As seen, the space between the primary beam axis and the deflected spot at 34 cm is mainly free of bremsstrahlung contributions and can be used to place the SRD to suppress hits from bremsstrahlung photons on them. Figure:3 shows the spatial distribution of the synchrotron photons at that position. During 2015 run the tagging of 100 GeV e\(^-\)’s by using prototype Pb-Sc SRD detectors (see, Sec. 2.7) to detect synchrotron radiation instead of BGO crystals was found to be effective at high intensity. A simple cut of about 1 MeV on the total energy deposit in SRD showed an efficiency of \(\gtrsim 95\%\) and it was possible to fully reject the few \% of hadrons contaminating the beam in good agreement with the suppression factor of \(10^{-3}\) calculated in the MC simulation. One may naively expect the suppression factor \(\sim 10^{-8}\) for heavy charged particles from the synchrotron radiation equation \((\Delta E \propto \frac{1}{m^4})\), where m is the mass.
Figure 2. The left panel shows the beam spot size at 13 m from the magnets on MM4 for a field of 1.8 T each for two magnets. Another plot shows the same distribution bremsstrahlung spot at 13 m from the magnets.

Figure 3. Synchrotron spot at 13 m from the magnets.

of the particle) but it is reduced to $\sim 10^{-3}$ due to the fact that these heavy charged particles like muons and pions may generate an energetic knock-on electrons, e.g. in the vacuum vessel windows, with energy larger than the applied cut. Finally the MC simulation suggest that the efficiency in a two magnet geometry will remain above 95% even when the selection cut is increased, this will give us the possibility to increase the suppression factor for heavy charged particle down to $10^{-5}$ without compromising the efficiency on the primaries, see Sec. 2.7.

The two MBPL magnets can be set up with fields identical to each other within $\approx 1\%$. A further way to calibrate the two magnets so as to not have any difference in their field effect the momentum resolution was also checked. Two different fields were taken for the two magnets, one with 1.8 T and the other with 1.6 T. The average deflection at MM3 and MM4 were checked to calculate the effective field due to the two magnets with 100 GeV and 80 GeV particles. The effective field was calculated to be $\sim 1.71$ T and this field was used to check the momentum of 100 GeV primary electrons in the same setup for a different run.
Figure 4. Preliminary design of the two vacuum pipes welded together to be used during beam time in July. Dimensions and design estimated taking into account the deflections in the field.

2.3 Vacuum Vessel

The required dimensions for the vacuum vessel were calculated and preliminary designs were made by the ETH group to discuss with the BD for production before our beam time in July. Two vacuum pipes as shown in Figure 4 are being planned to be used one inside the magnet and a bigger pipe of 11 m between the magnet and the MM3. Mylar Windows of 200 µm will be used to close the pipes on the two ends and the two pipes will be joined by flanges to avoid using another window. The design of these pipes has been discussed with BD and finalization of the design and their production is underway. The offsets have also been communicated to account for the deflections. The absorption of the SR photons by passive materials of the vessel is calculated to be negligible.

Figure 5. Strip Widths as designed for the new Micromegas modules

2.4 Micromegas

The Micromegas will measure the electron track upstream and downstream bending magnets. One of the new Micromegas modules with the modified strip widths as shown in Figure 5 has been received. This module, Figure 6, has been set up in the lab to test with a radioactive source, Sr90, which has an activity of 2.5 MBq and
emits 0.546 MeV $\beta^{-}$. The gas used for the chamber is a mixture of Ar-CO$_2$ (93-7%). Figure 7 shows the gain curve obtained for the new module, with the source, as a function of the amplification voltage. As seen a gain $\sim 10^4$ is obtained for voltage $\sim 520$ V. This voltage was used to check the hit efficiency of the detector. In order to check the efficiency of the detector the mesh signal from the detector was used as the trigger. The NA64 DAQ was integrated with the module and the strip signals were read using the DAQ after adding the analysis software for the module to the analysis software of NA64. Figure 8 shows the X (lhs) and Y (rhs) positions on the detector for the source signal. The plot is out of 10000 triggered events and as seen the efficiency is $\sim 94\%$ for a hit. The individual efficiency for the layers is: $X \rightarrow 94.5\%$, $Y \rightarrow 97.3\%$. The rest of the 4 modules (identical to the first) will be delivered on 21.06.2016. The modules were expected to be delivered mid of May but due to some problems at the production workshop at CERN the delivery was delayed. The assembly time for all the modules after their delivery is $\sim 2$ days following which we will need another 2-4 days for testing the modules.

Figure 6. New Micromegas module  

Figure 7. Gain curve as a function of the strip voltage.

Figure 8. X (lhs) and Y (rhs) Position on the detector from the source signal using the mesh as the trigger
The momentum reconstruction is shown in Figure 9 which shows a resolution of $\sigma \sim 0.74$ GeV. The improvement in the resolution is due to the fact that two magnets give larger deflection and thus better reconstruction of the radius. Also the deflection after the magnet are now used to reconstruct the radius (and hence the momentum from the calibrated field) instead of using the points in the radius of curvature of the particle inside the field and there is reduction of material (MM and vacuum windows) in the field to reduce secondary interactions. Thus this scheme to calibrate the two magnets seems to work and the momentum reconstruction also benefits from using two magnets. Shorter runs can be used during the beam time to calibrate the magnets even if their fields are not identical.

### 2.5 GEM

The electron tracks downstream of the bending magnet will be measured by two micropattern gaseous detectors based on the Gas Electron Multiplier (GEM) \cite{GEM}. The detectors have been built by the group of B. Ketzer at University of Bonn, Germany. Each of the detectors has an active area of $10 \times 10 \text{cm}^2$ and delivers two orthogonal projections of the particle trajectory. Fig. 10 shows a schematic front view of the detector, Fig. 11 a picture of two detectors behind each other mounted on a test setup in the laboratory.

The detectors have a triple-GEM amplification and will be operated at a gain of approx. 8000 in an Ar/CO$_2$ (70/30) gas mixture. The signals induced by charged particles traversing the detector are read out by four APV25-S1 chips. Each detector has two sets of 256 perpendicular strips at a pitch of 400 $\mu$m, i.e. 512 electronic
channels. The spatial resolution is expected to be of the order of 50 μm for each projection. The full readout chain has been taken over from the PixelGEM detectors of the COMPASS experiment and consists of front-end boards (dark grey rectangles in Fig. 10), a bus card on the detector (light green trapezoidal shapes), a custom-made ADC module capable of digitizing the signals from up to 16 APV chips, and a concentrator module (HGeSiCA).

The system was successfully tested with X-ray and β sources in the laboratory at the University of Bonn and will be shipped to CERN on Monday, June 20. The infrastructure required for the operation of the detectors (gas supply, support structures, HV supply) is currently being prepared at CERN.

2.6 Straw tubes

New straw chambers were manufactured with diam 20 x 200 straws covered by Cu layer. Each of coordinate plane consist of two layers of straw shifted each other to the size of the radius. Two mother board for different layers. New 6 Amplifier AST-1-1 (32 channels) for each coordinate which has to operate with 3 TDC units, are located directly on the camera stand. Cables are 17 twisted pairs, each of 60 cm in length. Since the test run 2015, the reconstruction of events in the straw tube tracker has been significantly improved.

- All straw camera was delivered in CERN, Meyrin site 154 building with clean room and low humidity. We will deliver the camera on the beam when assembled the gas system and blowing dry air for drying.
Figure 12. An event display example: hits (blue circles) in neighboring straw layers, crossed by beam particle (red line).

- 2 mm straw Station Straw Station (X and Y coordinates, 196 + 196 channels) was made with Cu-coated tubes. Straw Station (X and Y coordinates, 32 + 32 channels) was made with Carbon-coated tubes. One Spare Straw plane with 2mm tubes has been tested and work perfectly.

- 6 mm Straw Station These cameras worked on last run. Despite this, we had a full inspection and tested cameras.

- Preamplifiers Now the camera is equipped with new amplifiers developed in Belarus. The characteristics of the amplifiers we had not explored. We have tested only performance. These amplifiers are used in the experiment OKA (Protvino). The status of the equipment of TDS reported by Igor.

The 2mm straw tube tests have been performed with the analog preamplifiers without shaping of the output signal and by using for calibration the radioactive source Fe-55.

2.7 Fine-granularity Pb-Sc SRD detector

One of the key elements of the NA64 setup is the synchrotron radiation detector (SRD). The SRD was constructed to significantly improve purity for the incoming $e^-$ and enhance $\pi, \mu/e$ rejection. The SRD is a fine-granularity sandwich detector with lead and scintillators layers, which was specially developed for registration of synchrotron radiation from electrons with the energy $\gtrsim 50$ GeV. The structure of the SRD was choosen based on the careful simulations of the detector response. The main parameters for the optimal structure of the SRD detector are shown below:

(i) transverse size 18x8 cm$^2$, 3 modules 6x8 cm$^2$;

(ii) structure 250 layers lead + scintillators;

(iii) lead thickness 120 layers with 0.1mm and 130 layers with 0.2mm;
Figure 13. Preliminary results of 2mm straw tube tests i) 1 bar gas pressure; ii) 3 bar gas pressure. Carbon covered straw tubes; iii) 3 bar gas pressure. Cu covered straw tubes. Work point for good working amplifiers has to be 100 mV at H.V. of 1700V for Carbon straw tubes, and for Cu covered straw tubes at 1800 V.

(iv) scintillator thickness 1.1mm, read out with 1mm diameter WLS fibers, BCF91a;

(v) photosensor: green extended photomultiplier with the light yield 20 photoelectrons/MeV

In Fig.14 the simulated distribution of the SR energy deposited in the SRD by SR photons emitted by a 100 GeV electron beam is presented.

The energy spectra recorded by the SRD with electrons and pions are shown in Fig.14 and Fig.25 (see Sec. 3.4), respectively. The SR spectra obtained with the electron beam are used to perform the SRD calibration with the MIPs crossing the detectors and by comparing the spectra with the one predicted from simulations. As a cross check using the obtained calibration constants, the data from the pion beam impinging directly on the SRD are fit with a Landau distribution. The obtained peak position of 60 MeV is in good agreement with the prediction of the MC. With this method a very good agreement of data and MC within several orders of magnitude is achieved, see Fig. 14. Time coincidence of signals above the energy threshold and cuts on the energy deposition are further used for effective hadron and muon background rejection, see below Sec. 3.4.

2.8 The LYSO crystals

The detector was designed as a preshower for high resolution electromagnetic calorimeters with $\simeq 3 - 4%/\sqrt{E[GeV]}$ energy resolution. The schematic of the detector is shown in Fig.15.

The detector has 10x10 cm$^2$ sensitive area with 625 4x4x45 mm$^3$ (4X0) LYSO crystals. The read out is done with 1 mm diameter WLS fibers (Kuraray Y11) lattice
Figure 14. Distribution of the total energy deposited in the three SRD detectors from SR emitted by 100 GeV e⁻.

Figure 15. A schematic drawing of the LYSO SR calorimeter with one-sided readout.

and 50 SiPMs, silicone photomultipliers (HAMAMATSU Series S10931 MPPC, 3x3 mm³ sensitive area with 50x50 μm² pixel size). The mechanical layout is shown in Fig. 16.

The detector construction was completed in 2015. The fully-constructed detector view with 625 crystals assembled and WLS fiber read-out is shown in Fig. 16 (on the right). The estimated with the cosmic rays performance of the detector is shown in Fig. 17.
Figure 16. The detector mechanical layout (on the left). The detector view (on the right).

Figure 17. Sum of calibrated signals (in a.u.) from the X-WLS layer when a cosmic MIP particles cross the LYSO crystals resulting in $\simeq 88$ MeV energy deposition. The distribution shown has 12.6% FWHM, which corresponds to the array energy resolution $\simeq 3.7\%/\sqrt{E} [GeV]$.

2.9 The electromagnetic calorimeter

The search for $A' \rightarrow invisible$ events in NA64 relies strongly on electron identification as well as on a very accurate determination of the total missing energy in the incoming beam particle reaction. While electron identification is performed mostly by using the SRD, the electromagnetic calorimeter (ECAL) is crucial for accurate measurement of electron and gamma energies from 100 MeV up to 100 GeV and for the determination of the missing component of the full momentum. The high beam intensity and
large energy range to be covered requires use of a radiation hard detector with a large dynamic range in its and the associated electronics responses. A shashlik type ECAL was chosen for its radiation hardness, good energy resolution and uniformity of response. In NA64 the electromagnetic calorimeter combined with the Preshower Detector (PS) was also used to help improve the electron identification provided by the SRD. The ECAL consists of 36 shashlik counters arranged in a matrix with the following characteristics:

(i) It is a matrix of 6x6 cells, each with dimensions 38.2 × 38.2 × 490 mm³.

(ii) Each cell is (1.50 mm Pb + 1.50 mm Sc) x 150 layers of the total thickness \( T = 40 \) radiation length \( (X_0) \).

(iii) Each cell is longitudinally subdivided into two parts: preshower section (PS) of \( \approx 4 \ X_0 \) and the main ECAL of \( \approx 36 \ X_0 \).

(iv) The simulated energy resolution is \( \sigma E/E \approx 9\%/\sqrt{E(\text{GeV})} + 0.7 \).

The ECAL was calibrated with 100 GeV e⁻ beam by putting it on a movable table. The uniformity scan was also performed by using the tracker and the response was found to be very constant and uniform. A low-noise electronic chain, composed of a shaper followed by a sampling MSADC with a resolution of 12 bits, provides a calorimeter response in a dynamic range larger than \( 4 \times 10^3 \). In the left panel of Fig.18 the distribution of the total energy deposited in the PS and ECAL for the impinging 100 GeV e⁻ beam is shown. The distribution has Gaussian like shape and no significant energy leak or indication for the low-energy tail due to energy loss was observed. The transverse X-Y scan was used to determine the ECAL uniformity response and the e-m shower profile. In Fig. 18, right panel, the distribution of the variable \( \chi^2 = \Sigma(E_{ij}^m - E_{ij}^p)^2/(E_{ij}^m)^2 \) is shown, which was also used for the e⁻ identification. Here, \( E_{ij}^{m(p)} \) is the measured(predicted) shower energy in the ij-cell for the given incoming coordinate of the e⁻ track in the ECAL. The ECAL instability effects was taken into account by measurements the response to the monitoring LED performed during the whole run. The linearity of the calorimeter response to electrons was verified at the test beam in the energy range 30-100 GeV. Deviations from linearity were found to be below a few %. The e-m shower profile was used to determine the X-Y coordinate of the incoming electron in the ECAL. The difference between the predicted and measured X-positions of a 100 GeV e⁻ was found to be determined typically with the resolutions of the order of 1-3 mm depending on X.

### 2.10 The hadronic calorimeter

The HCAL is used to enhance the longitudinal setup hermeticity for the sensitive search for the invisible decay \( A' \rightarrow \chi \bar{\chi} \) into the lighter dark matter particles. The Hadron Calorimeter (HCAL) is intended to detect charged and neutral hadrons and
to provide a measurement of the energy leak from the ECAL complementary to that derived from momentum measurements in the tracker chambers and the ECAL itself. Knowledge of neutral hadrons energy is important when constructing kinematic variable such as missing energy, as Veto cannot reject events with a neutral hadronic final stat. HCAL calorimetric measurements of charged particles can be also used both as a consistency check on the momentum measurement of the incoming charged particles and as an aid in distinguishing between muons and charged hadrons.

The HCAL consists of 4 modules, each of 9 cells arranged in a matrix 3x3. Each cell consists of 48 iron/scintillator layers with 25 mm and 4 mm thickness, respectively. The iron plates are spot-welded together providing appropriate mechanical rigidity. Each module has transverse dimension of $60 \times 60 \text{ cm}^2$, weight 3500 kg and corresponds to about $7 \lambda_{int}$ (nuclear interaction lengths). Light read-out is provided by Kyraray Y11 WLS-fibers embedded in round grooves in the scintillator plates. The WLS-fibers from each of 9 cell scintillator tiles are collected together in a single optical connector of the module read-out by a single photomultiplier (PMT FEU-84). The counter also have longitudinal segmentation into 4 sections ensures good time uniformity of light collection along the module from the observed particle shower. Nine PMTs per module are placed at the rear side of the module together in a box with the front-end-electronics. Monitoring of the HCAL cells response is performed using green Light Emitting Diodes (LED) per counter mounted on the same box with PMTs.

The HCAL modules have been calibrated individually by putting each on a movable platform with a subsequent irradiation of the HCAL cells with 100 GeV electron and 80 GeV pion beams. The dependence of obtained energy resolution on beam energy in the energy range 10 - 100 GeV is given by $\sigma_E/E = 0.57 \sqrt{E} + 0.037$. The peak of the minimum-ionizing distribution, which has the expected Landau shape is at $\approx 2.5$ GeV in agreement with MC prediction and calibration measurements. For events

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**Figure 18.** The distributions of the total energy deposited in the PS and ECAL for the impinging 100 GeV $e^+$ beam.
from hadron electro-production or when hadrons begin to shower in the approximately 1.2 $\lambda_{int}$ of ECAL upstream of the hadron calorimeter, the total hadronic energy deposited in the ECAL+HCAL system is taken to be a weighted sum of the energies deposited separately in the hadron and electromagnetic calorimeters.

2.11 VETO

The veto system consists of an arrangement of three scintillation counters covering an area of $\simeq 60 \times 60$ cm$^2$ at the downstream end of the ECAL detector. The scintillators have a thickness of 2 cm, a width of 21 cm, and are of the length 60 cm. The counters are viewed at both ends by photomultipliers XP2020Q. The counters are arranged in a geometry which provides optimal rejection of charged particles escaping the ECAL. The two photomultiplier outputs connected to each veto counter are fed via discriminators to the inputs of mean-timer modules, the timing of which provides an output signal independent in time of the position at which the detected charged particle traversed the counter. The signals from these counters are recorded in MSADC and are available on-line. The charged particle rejection efficiency of the veto is constantly monitored and has remained stable within a few %.

2.12 Electronics

The DAQ was successfully commissioned last year. This year it will be extended to read out the following detectors:

- about 200 channels of the ECAL and HCAL calorimeter;
- 1280 channels of Straw detector;
- 96 channels of hodoscopes;
- 50 channels of the LYSO SRD;
- up to 2000 channels of MM and GEM detectors using APV ASIC;

The current status of the DAG and front-end electronic is the following:

(i) Electromagnetic Calorimeter: The readout chain of the electromagnetic calorimeter consists of MSADC, Shaper, and Data Concentrator module.
- all 17 MSADC modules have been tested and 16 of them are working fine;
- all 8 shaper modules have been produced, - all 4 CC4MSADC carrier cards have been tested and are working; All ECAL working cards will be delivered to CERN beginning of this week for assembly in the beam area.

(ii) Straw front-end electronics: The Straw tubes will be equipped with preamplifier-discriminator cards developed for CBM experiment and based on OKA-1 ASIC. The cards already exist, see Fig.19 A dedicated TDC card for NA64 experiment
based on an FPGA has been developed. The first prototype was tested, and the order for NA64 TDC production has been submitted yesterday and currently they are in production. The delivery is expected delivery by June 21.

![Figure 19. Photograph of the preamplifiers](image)

(iii) Hodoscope TDC and beam counter TDC: A TDC for hodoscope detectors as well as for beam counters is a faster version of the straw TDC. They are will be produced simultaneously with the straw TDC.

(iv) MM and GEM detectors: The front-end electronics of MM and GEM detectors is ready for installation.

3 Search for the $A' \rightarrow \text{invisible decay}$

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 $E_{\text{miss}} = E_{A'} = E_0 - E_e$ above those expected from backgrounds. Here we assume that the $\chi$s have to traverse the detector without decaying visibly in order to give a missing energy signature. No other assumptions on the nature of the $A' \rightarrow \text{invisible}$ decay are made. The signal candidate events have the signature:

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

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 $f \lesssim 0.8$, see energy spectra in Fig. 41, and discussion below. 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.
3.1 Signal simulation

Throughout this experiment, we have relied on two codes: NA64 [10] for simulation of dark photon production and decays, and GEANT4 [21] for propagation of produced secondaries and decay particles through the detector. In this report, we base our comparison with data on these two codes, and we also anticipate that comparison of dimuon results, see Sec. 4, will follow in the near future.

In order to determine the acceptance of the experiment we perform the signal Monte Carlo simulation as described in details in Ref.[10]. We simulate the electromagnetic shower development in the ECAL with GEANT4 using the following steps:

(i) calculate the total and differential cross-sections of the $A'$ bremsstrahlung production as a function of the electron energy $E_0$,

(ii) at each step of an electron propagation in the lead converters of the ECAL, the emission of the $A'$ is randomly generated,

(iii) if the emission is accepted, then we generate values of $x$, $\cos \theta$, and the azimuthal angle $\phi_{A'}$,

(iv) finally, the 4-momentum of the recoil electron is calculated.

At the final simulation stage, the cross section is multiplied by an additional factor so that about 0.1 $A'$ per one event is produced. This factor is later used for the final normalization.

In Fig. 20 an example of the $A'$ energy distributions calculated for masses $m_{A'} = 10$ MeV and $m_{A'} = 500$ MeV are shown. Note that these distributions represent also the missing energy spectra in the detector.

3.2 Single $e^-$ track selection

After establishing the efficiency, spatial and timing resolution of the MM modules, the tracking of the incoming particles was done under an integrated magnetic field of 7 T.m over two magnets with a combined length of 4.8 m with the four modules, to select the incoming tracks. The cluster multiplicity (no. of clusters/plane/event) was also checked for different beam fluxes to suppress pile up events. Figure:21 shows the distribution of the cluster multiplicity for different beam intensities. As seen from the plot with higher fluxes the number of events with $> 1$ signal cluster on each projection increases due to pile up in time. There are $\sim 6\%$ events with $>1$ signal cluster on each projection for the maximal beam intensity. A cut on the cluster multiplicity (requiring one cluster/projection for each event) was used to suppress pile up events in the MM modules. Figure:22 shows the reconstructed momentum for a 100 GeV/c electron beam as obtained with the Genfit software (a generic track reconstruction framework for nuclear and particle physics). The resolution of the central peak is $\sim$
Figure 20. The $A'$ emission spectrum from 100 GeV electron beam interactions in the Pb target calculated for $m_{A'} = 10$ MeV and $m_{A'} = 500$ MeV. The spectra are normalized to about the same number of events.

Figure 21. No. of clusters/event in X (left) and Y (right) plane for different beam flux 1.2 GeV/c as shown in the plot. The momentum reconstruction was also checked as a function of the incoming beam angle. Figure:23 shows a sketch of the incoming beam. The angle of the incoming beam with respect to the z-axis was calculated from the MM1 and 2 hits and the reconstructed momentum was plotted as a function of the angle as shown in Figure:24. In principle higher and lower momentum particles should not be within the acceptance of the geometry unless they enter with large
Figure 22. Reconstructed momentum with the four Micromegas modules for a 100 GeV/c beam. The black histogram is data and the red line is a fitted Gaussian function with parameters “Sigma” and “Mean”

incident angles with respect to the primary beam direction. As expected when the initial deflection is in the positive x direction the reconstructed momentum is larger with increasing angle and when the initial deflection is in the negative x direction the reconstructed momentum tends to be smaller with increasing angle. Therefore, an angular cut to select parallel incoming tracks measured by the 2 MMs (MM1, MM2) upstream the magnet along with a cut of 100 GeV/c ± 5 GeV on the reconstructed momentum was used to reject the low energy tail of beam electrons.

3.3 $e^-$ identification

The search for $A' \rightarrow \text{invisible}$ events in NA64 relies strongly on electron identification which is performed by using the Synchrotron Radiation Detectors, see Section 2.7, and ECAL. The total energy spectrum recorded by the SRD BGO used in July run with 100 GeV electrons is shown in Fig.14. For the electron spectrum, a 1% pileup events have been added to the simulation as predicted for the given spill intensity and with the known decay time of SRD. The spectrum are in very good agreement with the simulation. The $e^-$ events were selected by requiring:

(i) the presence of the energy deposition $1 < E_{SRD_i} < 60$ MeV in each SRD$_i$ module, i=1,2,3.

(ii) the total energy must be $\Sigma SRD_i < 80$ MeV

(iii) all SRD$_i$ signals must be in-time within ±2 ns with the trigger counter S0.
Figure 23. Example of incoming beam deflection. Incoming angle is calculated with respect to the Z-axis.

Figure 24. Momentum reconstructed as a function of the incoming angle for incoming particle deflected towards the positive x axis (left) and negative x axis (right).

The SR spectra obtained with the electron beam are used to perform the SRD calibration. The obtained calibration constant were cross checked with the energy deposited by the MIPs crossing the SRD detectors by fitting the spectra to Landau distribution and comparing them with the one predicted from simulations. The obtained peak position of 60 MeV is in good agreement with the prediction of the MC. With this method a very good agreement of data and MC within several orders
of magnitude is achieved, see Fig. 14. The cut on the SRD energy deposition was effective to suppress the low energy events from upstream interactions with the beamline materials.

3.4 Hadron and muon rejection

The SRD spectrum recorded with the 100 pion beam is shown in Fig. 25. The spectrum are in very good agreement with the simulation. The time coincidence of signals from all three SRD counters was very effective to remove possible background due to hadron or muon decays in flight. The suppression by synchrotron radiation emission detected for pions compared to electrons dramatically increased by using the condition i), as is clearly seen by comparing the two plots shown in Fig. 26. Here the distribution of energy deposited in the HCAL by 100 GeV $\pi^-$ impinging on the ECAL for events selected without (left panel plot) and with (right panel plot) SRD tag. An admixture of events with a large energy deposition form hadron contaminated the beam is vanished in the right panel plot, where only events with the energy deposited by hadronic secondaries from the $\pi^-$ hadronic interactions in the ECAL are present.

The electron-hadron separation can be further improved by using variables describing i) the electromagnetic shower development at an early stage by using the ECAL preshower section, and ii) lateral shower profile as described in details in Ref. [10], where the questions how identical are the longitudinal development of showers induced by the signal reaction (5.1) and by an ordinary electron and how the applied hadron rejection cuts affect the signal efficiency are also studied.

An example of variable used for electron identification and hadronic background suppression is illustrated in the right panel in Fig. 18, where the distribution of

Figure 25. Distribution of energy deposited in the SRD detector from SR emitted by 100 GeV $\pi^-$. 

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>451164</td>
<td>0.3943</td>
<td>1.673</td>
</tr>
</tbody>
</table>
Figure 26. Distribution of energy deposited in the HCAL by 100 GeV $e^-$ impinging on the ECAL for events selected without (left plot) and with (right panel plot) the requirement of the SRD tag.

$$\chi^2 = \Sigma (E_{ij}^m - E_{ij}^p)^2/(E_{ij}^m)^2$$ is shown. Here, $E_{ij}^m(p)$ is the measured(predicted) shower energy in the cell $ij$ for the given incoming coordinate of the $e^-$ track in the ECAL.

For the above criteria the overall suppression factor for the pions was $\lesssim 10^{-6}$, while the efficiency for the electrons detection was higher than $95\%$.

3.5 Data sample and results from July run

The events were collected with the hardware trigger of (3.1) requiring an in-time cluster in the ECAL with the energy $E_{ECAL} \lesssim 80$ GeV. The results reported here came mostly from a set of data in which $n_{EOT} = 1.88 \times 10^9$ of electrons on target (eot) were collected with the beam intensity $\simeq 1.4 \times 10^6$ $e^-$ per spill with the PbSc calorimeter. A smaller sample of $n_{EOT} = 0.87 \times 10^9$ and an intensity $I_e = 0.3 \times 10^6$ $e^-$ was also recorded with the BGO detector. Data of these two runs (hereafter called the BGO and PbSc run) were analyzed with similar selection criteria and finally summed up, taking into account the corresponding normalization factors.

3.5.1 Background estimate

The search for the $A' \rightarrow invisible$ decays requires particular attention to backgrounds. Every process with a track and a single e-m cluster in the ECAL was considered as a potential source of background. There are several sources which may fake the $A' \rightarrow invisible$ signal, e.g., $e^-$ interactions with the beam line materials resulting in $e^-$ energy loss, $\mu \rightarrow e\nu\nu$, $\pi/K \rightarrow e\nu$, $K_{e3}$ decays in flight, energy leakage from particle punchthrough in the HCAL, processes due to pileup of two or more particles, and instrumental effects due to energy loss through cracks in the upstream detector coverage. The selection cuts to eliminate these backgrounds have been chosen such that they do not affect the shape of the true $E_{miss}$ spectrum.

Two independent methods were used for the background estimation in the signal region. The first method is based on the MC simulations. Because of the small $A'$
coupling strength, the fraction of reactions (2.1) is typically $\lesssim 10^{-9}$ per incoming $e^-$. To study the SM distribution and background at this level is very time consuming. Consequently, we have evaluated with MC simulations all known backgrounds to the extent that it is possible. Events from particle interactions or decays in the beam line, pileup activity created from them, hadron punchthrough from the target and the HCAL were included in the simulation of background events. Small event-number backgrounds such as the decays of the beam $\mu, \pi, K$ or $\mu$ from the reaction of dimuon production were simulated with the full statistics of the data. Large event-number processes, e.g. from $e^-$ interactions in the target or beam line, punchthrough of secondary hadrons were also studied extensively, although simulated samples with statistics similar to the data were not feasible. To eliminate possible instrumental effects not present in the MC calculations, the uniformity scan of the central part of the ECAL target was performed with $e^-$ by using T3 and T4.

The two largest sources of background are expected from the beam $\mu, \pi, K$ decays in flight. In one case, e.g. when a pion passes through the vacuum vessel it could knock electrons off the downstream window, which hit the SRD creating a fake tag for a 100 GeV $e^-$. Then the pion could decay into $e\nu$ in the upstream ECAL region thus producing the fake signal. Similar background is caused by the pileup of an electron from the low-energy beam tail ($\lesssim 60-80$ GeV) and a beam $\mu, \pi$, or $K$. The electron could emit the amount of SR energy above the threshold which is detected in the SRD as a tag of 100 GeV $e^-$ and then is deflected by the magnets out of the detector’s acceptance angle. While the accompanied muon or hadron could then decay in flight. For both sources the dominant background came from the $K_{e3}$ decays. The mistakenly tagged $\mu$, and $\pi$ and $K$ could also interact in the target producing an e-m like cluster below 50 GeV though the $\mu Z \rightarrow \mu Z \gamma$ or $\pi, K$ charge-exchange reactions, accompanied by the poorly detected scattered $\mu$, or secondary hadrons, respectively. Another background is due to $e^-$ interactions in the beam line. Table I summarizes the conservatively estimated background inside the signal box, which is expected to be $0.15 \pm 0.03$(stat) $\pm 0.06$(syst) events. The systematic error includes the uncertainties in the amount of passive material for $e^-$ interactions, and in the cross sections of the $\pi, K$ charge-exchange reactions on lead (30%).

The second method used the background estimate extracted from the data themselves. MC signal events and the background extrapolated from sidebands A and C shown in the right panel of Fig. 27 were used. Events in the region A ($E_{ECA} < 50$ GeV; $E_{HCA} > 1$ GeV) are pure neutral hadronic secondaries produced by electrons in the ECAL target, while events from the region C ($E_{ECA} > 50$ GeV; $E_{HCA} < 1$ GeV) are likely from the $e^-$ interactions in the downstream part of the beam line accompanied by bremsstrahlung photons absorbed in the HCAL. The yield of the background events was estimated by extrapolating the observed events to the signal region assessing the systematic uncertainties by varying the
background fit functions. Possible variation of the HCAL zero-energy threshold during data taking were also taken into account. Using this, we obtained a second background estimate of $0.4 \pm 0.3$ events. The background estimates with the two methods are in agreement with each other within errors. After determining all the selection criteria and estimating background levels, we examined the events in the signal box and found no candidates, as shown in Fig. 27. The conclusion that the background is small is confirmed by the data.

### 3.5.2 Sensitivity evaluation

![Figure 27](image.png)

**Figure 27.** The left panel shows the measured distribution of events in the ($E_{ECAL}; E_{HCAL}$) plane from the combined BGO and PbSc run data at the earlier phase of the analysis. Another plot shows the same distribution after applying all selection criteria. The dashed area is the signal box region which is open. The side bands A and C are the ones used for the background estimate inside the signal box. For illustration purposes the size of the signal box along the $E_{HCAL}$ axis is increased by a factor of 5.

The events were collected with the hardware trigger requiring an in-time cluster in the ECAL with the energy $E_{ECAL} \lesssim 80$ GeV. The results reported here came mostly from a set of data in which $n_{EOT} = 1.88 \times 10^9$ of electrons on target (eot) were collected with the beam intensity $\simeq 1.4 \times 10^6$ e$^-$ per spill with the PbSc calorimeter. A smaller sample of $n_{EOT} = 0.87 \times 10^9$ and an intensity $I_e = 0.3 \times 10^6$ e$^-$ was also recorded with the BGO detector. Data of these two runs (hereafter called the BGO and PbSc run) were analyzed with similar selection criteria and finally summed up, taking into account the corresponding normalization factors.

In order to avoid biases in the determination of selection criteria for signal events, a blind analysis was performed. Candidate events were requested to have the missing energy in the range $50 < E_{miss} < 100$ GeV, which was selected based on the calculations of the energy spectrum of $A$'s emitted in the reaction (2.1) by $e^\pm$ from the e-m
shower generated by the beam $e^-$s in the target [10]. The HCAL zero-energy thresh-
old was selected to be $E_{HCAL} = 1$ GeV, and was determined mostly by the noise of the 
read-out electronics. Events from a signal box ($E_{ECAL} < 50$ GeV; $E_{HCAL} < 1$ GeV) 
were excluded from the analysis of the data until the validity of the background es-
timate in this region was established. For the selection criteria optimization, 10% of 
the data were used, while the full sample was used for the background estimate. The 
number of signal candidate events were counted after unblinding. A detailed Geant4 
based Monte Carlo (MC) simulation was used to study the detector performance 
and acceptance, to simulate background sources, and to select cuts and estimate the 
reconstruction efficiency.

The left panel in Fig. 27 shows the distribution of $\simeq 5 \times 10^4$ events from the 
reaction $e^-Z \rightarrow \text{anything}$ in the ($E_{ECAL};E_{HCAL}$) plane measured with $2.75 \times 10^9$ 
eot. Here, $E_{HCAL}$ is the sum of the energy deposited in the first two HCAL modules. 
Only the presence of a beam $e^-$ identified with the SR tag was required. Events 
from the area I in Fig. 27 originate from the QED dimuon production, dominated by 
the reaction $e^-Z \rightarrow e^-Z\gamma;\gamma \rightarrow \mu^+\mu^-$ of the muon pair photoproduction by a hard 
bremsstrahlung photon conversion on a target nucleus and characterized by the en-
ergy of $\simeq 10$ GeV deposited by the dimuon pair in the HCAL. This rare process 
was used as a benchmark allowing to verify the reliability of the MC simulation, estimate 
the signal reconstruction efficiency, and cross-check systematic uncertainties, See Sec 
4 for more details. The dimuon production was also used as a reference for the 
background prediction. The region II shows the SM events from the hadron electro-
production in the target which satisfy the energy conservation $E_{ECAL}+E_{HCAL} \simeq 100$ 
GeV within the energy resolution of the detectors. The leak of these events to the 
signal box due to the energy resolution was found to be negligible. The events from 
the region III whose fraction is a few $10^{-2}$ are mostly due to pileup of $e^-$ and beam 
hadrons.

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. 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 the SRD detector 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 [10]. (iv) There should be no activity in V2. Only $\simeq 300$ events passed these 
criteria from combined BGO and PbSc runs.

The $m_{A'}$-dependent upper limit on the mixing $\epsilon$ is calculated as follows. For a 
given number $n_{EOT}$ and the mass $m_{A'}$, the number of signal events $N_{A'}$ expected
Table 1. Expected numbers of background events in the signal box that passed the selection criteria i)-iv) estimated for $2.75 \times 10^9$ eot.

<table>
<thead>
<tr>
<th>Source of background</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>loss of $e^-$ energy due to punchthrough $\gamma$s</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>loss of hadrons from $e^-Z \to e^- + hadrons$</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>loss or $\mu \to e\nu\nu$ decays</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>of muons from $e^-Z \to e^-Z\gamma; \gamma \to \mu^+\mu^-$</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>$e^-$ interactions in the beam line materials</td>
<td>0.03</td>
</tr>
<tr>
<td>$\mu \to e\nu\nu, \pi/K \to e\nu, K_{e3}$ decays</td>
<td>0.03</td>
</tr>
<tr>
<td>followed by their decays</td>
<td>0.05</td>
</tr>
<tr>
<td>$\mu, \pi, K$ interactions in the target</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Figure 28. The NA64 90% C.L. exclusion region in the $(m_{A'}, \epsilon)$ plane. Constraints from the BaBar, and E787+E949 experiments, as well as the muon $\alpha_{\mu}$ favored area are also shown. Here, $\alpha_{\mu} = \frac{g_{\mu}-2}{2}$. For more limits obtained from indirect searches and planned measurements see e.g. Ref. [2]. The picture is adapted from [28].

from the reaction (2.1) in the signal box is given by:

$$N_{A'} = n_{EOT} \times n_{A'}(\epsilon, m_{A'}, \Delta E_{A'}) \times \epsilon_{A'}(m_{A'}, \Delta E_{A'})$$  \hspace{1cm} (3.2)

where $n_{A'}(\epsilon, m_{A'}, \Delta E_{A'})$ is the yield of $A'$s with the coupling $\epsilon$, 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 \cite{10}. These events correspond to the missing energy \(0.5 E_0 < E_{\text{miss}} < E_0\). 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 (\(\approx 0.8\)), veto V2 (0.96) and HCAL signal efficiency (0.94) and the acceptance loss due to pileup (\(\approx 8\%\) for BGO and \(\approx 7\%\) for PbSc runs). The number of collected \(n_{\text{EOT}} = 2.75 \times 10^9\) 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 \cite{10}. The \(A'\) yield calculated as described in Ref.\cite{10} was cross-checked with calculations of Ref.\cite{27}. The \(\approx 10\%\) discrepancy between these two calculations was accounted for as systematic uncertainty in \(n_{A'}(\epsilon, m_{A'}, \Delta E_{A'})\) due to a possible difference in treatment of the e-m shower development. 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 \(E_{\text{ECAL}} \lesssim 60\) GeV was made, resulting in additional \(\approx 20\%\) uncertainty in the dimuon yield, see Sec.4.

The V2 and HCAL signal efficiency was defined as a fraction of events below the corresponding zero-energy thresholds. The shape of the energy distributions in these detectors from the leak of the signal shower energy in the ECAL was simulated for different \(A'\) masses \cite{10} and cross-checked with measurements at the \(e^-\) beam. The uncertainty in the V2 and HCAL efficiency for the signal events, dominated mostly by the pileup effect from penetrating hadrons in the high intensity PbSc run, was estimated to be \(\approx 3\%\). Finally, the dominant source of systematic uncertainties on the expected number of signal events comes from the uncertainty in the estimate of the yield \(n_{A'}(\epsilon, m_{A'}, \Delta E_{A'})\) (19\%). 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.(5.9) into account and using the relation \(N_{A'}(m_{A'}) < N_{A'}^{90\%}(m_{A'})\) results in the 90\% C.L. exclusion area in the \((m_{A'}; \epsilon)\) plane shown in Fig. 28. These results exclude the invisible \(A'\) as an explanation of the muon \(g-2\) anomaly for the masses \(m_{A'} \lesssim 100\) MeV. The further improvement in sensitivity on \(\epsilon\) for the background-free case scales as \(1/\sqrt{n_{\text{EOT}}}\). Moreover, the results obtained allow us to restrict other models with light scalars interacting with electrons and decaying predominantly to invisible modes.
3.6 Data sample and preliminary results from October run

The October run was divided into two data-taking periods, of which the first one used for the $A' \rightarrow \text{invisible}$ running and the second one for the feasibility study of the rare decay $X \rightarrow e^+e^-$, see Sec. 5. The first period was subdivided into three different runs with gradually increased intensity of the electron beam in order to study the feasibility of the search for the $A' \rightarrow \text{invisible}$ 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:

- $n_{\text{eot}} \simeq 2.0 \cdot 10^{10}$ eot with intensity $\simeq 2 \cdot 10^6 e^-$/spill
- $n_{\text{eot}} \simeq 1.2 \cdot 10^{10}$ eot with intensity $\simeq 3.5 \cdot 10^6 e^-$/spill
- $n_{\text{eot}} \simeq 0.9 \cdot 10^{10}$ eot with intensity $\simeq 5 \cdot 10^6 e^-$/spill

were recorded.

(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 October 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 (3.1) requiring an in-time cluster in the ECAL with the energy $E_{\text{ECAL}} \lesssim 80$ 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 [10]. (iv) There should be no activity in V2. About $\simeq 10^4$ events passed these criteria.

![Figure 29](image)

Figure 29. The left panel shows the measured distribution of events in the $(E_{ECAL};E_{HCAL})$ plane from the runs 2288-2361 taken an the beam intensity $\simeq 2 \cdot 10^6$e-/spill. The right panel plot shows similar events distribution for the maximal intensity of $\simeq 5 \cdot 10^6$e-/spill. Both plots are shown after applying all selection criteria. The the signal box, which is open for these selected samples of events, corresponds to the region $E_{ECAL} < 0.5E_0; E_{HCAL} < 1$ GeV.

For the data from October run significant effort has gone into studying performance of the detector at high beam rate. Following the July run, we observed that we had been operating with a lower efficiency for single beam electrons identification in the detector than in July run. This efficiency, combined with online MM tracking code that was based on July off-line tracker performance, led up to 30% loss of efficiency during the October run at the beam intensity $\simeq 5 \cdot 10^6$e-/spill, resulting to the overall efficiency $\simeq 0.3$, which is more than a factor 2 lower compared to the value 0.67 obtained for the beam rate $\simeq 10^6$e-/spill. Offline studies have shown that the loss of events is 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 $A' \rightarrow invisible$ search. After several months of work, we were able to substantially improve the overall efficiency from 0.32 to 0.70 for high-intensity runs, by implementing the specially developed pileup removal algorithm. This was achieved so far without considering the MM tracker. We still continue working on the pileup removal algorithm and the final way to correct the pileup in 2016 data without substantial decreasing the overall efficiency in the result and reduction of the sensitivity. The approach we develop is based on the use of the detector signal shape.
Similar to the July run, the selection criteria and requirements for the October 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 \( n_{EOT} = (3 - 5) \times 10^9 \) of electrons on target (eot) were collected with the beam intensity \( \simeq (2 - 3) \times 10^6 \) e\(^-\) per spill. A smaller sample of \( n_{EOT} = 3 \times 10^8 \) and an intensity \( I_e = 5 \times 10^6 \) e\(^-\) was also analysed. Data of these two runs were analyzed with similar selection criteria. In Fig.29, the left panel shows the measured distribution of events in the \((E_{ECAL}; E_{HCAL})\) plane from the runs 2288-2361 taken an the beam intensity \( \simeq 2 \cdot 10^6 \) e\(^-\) / spill. The right panel plot shows similar events distribution for the maximal intensity of \( \simeq 5 \cdot 10^6 \) e\(^-\) / spill. Both plots are shown after applying all selection criteria. The signal box, which is open for the selected samples of events comprising about 20% of the data sample, corresponds to the region \( E_{ECAL} < 0.5E_0; E_{HCAL} < 1 \) GeV. In this measurement, one of the major sources of the systematic error are supposed to be the uncertainties associating the absolute flux of dark photons from the active dump and the detector response. In the previous July measurements by the NA64, the \( A' \) yield were estimated by means of Monte Carlo simulations using the experimentally determined ratios of dimuons from the reaction \( e^-Z \rightarrow e^-Z\mu^+\mu^- \) per incident electron, and the uncertainties in the \( A' \) yield were not smaller than 7%, being greater than statistical errors of those experiments. A more

<table>
<thead>
<tr>
<th>Cut</th>
<th>number of events</th>
<th>Efficiency, ( n_{i+1}/n_i )</th>
<th>Rejection factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial number of events</td>
<td>582897</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>Trigger time window</td>
<td>573477</td>
<td>0.99</td>
<td>0.01</td>
</tr>
<tr>
<td>ECAL, HCAL time window</td>
<td>573477</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>( e^- ) hits ECAL central cell</td>
<td>561747</td>
<td>0.98</td>
<td>0.02</td>
</tr>
<tr>
<td>SRD time and energy window</td>
<td>556203</td>
<td>0.99</td>
<td>0.01</td>
</tr>
<tr>
<td>Veto time and energy window</td>
<td>420402</td>
<td>0.76</td>
<td>0.24</td>
</tr>
<tr>
<td>ECAL pileup events</td>
<td>410251</td>
<td>0.97</td>
<td>0.04</td>
</tr>
<tr>
<td>Shower shape</td>
<td>404478</td>
<td>0.98</td>
<td>0.02</td>
</tr>
<tr>
<td>MM ( \Delta X, Y )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM time window (prompt 100 ns)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incoming angle cut</td>
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</tr>
<tr>
<td>Outcoming angle cut</td>
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<td></td>
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</tr>
<tr>
<td>Track momentum ( \Delta P )</td>
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</tr>
<tr>
<td>total</td>
<td>404478</td>
<td>0.69</td>
<td>0.31</td>
</tr>
</tbody>
</table>
Figure 30. The expected NA64 90% C.L. exclusion region in the $(m_{A'}, \epsilon)$ plane from the October run, dashed curve labeled $4 \times 10^{10}$. See, also Fig. 28.

accurate determination of the $A'$ yield may be achieved by directly measuring the rates of the dimuon reactions, whose cross-sections are known with accuracy of 2% [41]. This kind of measurement will need an additional scintillation counter located near the active target of NA64. For precise understanding of the detector response, we will develop movable counter in the active volume for calibrations of the position and energy measurements.

3.7 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. The most popular vector mediator model is the model with additional massive photon $A'$ which couples with dark matter particles via interaction $L_I = g_D A'_\mu J^\mu_{DM}$ with coupling constant $g_D (\alpha_D \equiv \frac{g^2_D}{4\pi})^{1}$. The mixing $L_{mix} = -\frac{1}{2} \epsilon F_{\mu
u} F'_{\mu
u}$ between photon field $A_\mu$ and dark photon field $A'_\mu$ leads to nonzero interaction of dark photon $A'_\mu$ with the electrically charges SM particles with the charges $e = e_{SM}$. So as a result of mixing the annihilation cross-section of DM particles is proportional to $\epsilon^2$. The dark matter

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

---

1The currents $J^\mu_{DM} = \bar{\psi}_{DM} \gamma^\mu \psi_{DM} \quad \text{and} \quad J^{\mu\nu}_{DM} = i(\phi^{+}_{DM} \partial^\mu \phi_{DM} - \phi_{DM} \partial^\mu \phi^{+}_{DM})$ for spin 1/2 and 0.
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 $v_{\text{rel}} \ll c$ is

$$\sigma v_{\text{rel}} = \frac{8\pi}{3} \frac{\epsilon^2 \alpha_D m_\phi^2 v_{\text{rel}}^2}{(m_{A'}^2 - 4m_\phi^2)^2 + m_{A'}^2 \Gamma^2}, \quad (3.3)$$

where $\Gamma$ 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 matter mass $m_\phi$ and the dimensionless variable

$$y \equiv \epsilon^2 \alpha_D \frac{m_\phi}{m_{A'}}^4, \quad (3.4)$$

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

$$\sigma v_{\text{rel}} = \frac{8\pi}{3} \frac{\epsilon^2 \alpha_D m_\phi^2}{(m_{A'}^2 - 4m_\phi^2)^2 + m_{A'}^2 \Gamma^2}. \quad (3.5)$$

Note that the absence of $v_{\text{rel}}^2$ factor in (3) is due to the fact that the annihilation of fermions takes place in the s-wave. Numerically for $v_{\text{rel}} \sim 1/3$ the annihilation cross-section for scalar dark matter is suppressed by factor $\sim 25$ in comparison with fermion dark matter( for the same mass and $\alpha_D, \epsilon$). For the axial-vector interaction we have p-wave suppressed annihilation with $\sigma v_{\text{rel}} \sim v_{\text{rel}}^2$, as for the scalar case. If the global $U'(1)$ symmetry under which the Weyl components $\phi_{1,2}$ of Dirac fermion $\phi = (\phi_1, \phi_2)^T$ have opposite charges is broken(by a Higgs field that gives mass to the $A'$) the interaction $L_{\text{break}} = \delta \phi_1 \phi_2$ yeld mass eigenstates $\phi_\pm = \frac{1}{\sqrt{2}}(\phi_1 \pm \phi_2)$ split in mass by $\delta$. 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 inelastic fermion dark matter models survive. From the equations (2,3) we can estimate the value of $y$. Namely, for fermion dark matter we find

$$y = \frac{m_\psi^2}{8\pi \alpha} \cdot \frac{1}{(1 - \frac{4m_\psi^2}{m_{A'}^2})^2}. \quad (3.6)$$

\(^2\)Here $f$ is the SM particle.
Numerically, for $<\sigma v> = 0.3 \cdot 10^{-8}\text{GeV}^{-2}$ we find that

$$y = 1.6 \cdot 10^{-12}(m_\psi/10 \text{ MeV})^2 \cdot (1 - \frac{4m_\psi^2}{m_{A'}^2})^2$$ (3.7)

For scalar dark matter the corresponding estimate reads

$$y = 0.4 \cdot 10^{-10}(m_\psi/10 \text{ MeV})^2 \cdot (1 - \frac{4m_\psi^2}{m_{A'}^2})^2$$ (3.8)

---

**Figure 31.** Constraints in the $(\alpha_D;m_{A'})$ plane on the Pseudo-Dirac (the left panel) and Majorana (right panel) type light thermal Dark Matter. The NA64 curves represent the constraints obtained from the July (magenta solid) and projected combined limit from the 2016(magenta dashed) runs. The plots are reproduced from [29].

---

4 Dimuon events from the reaction $e^- Z \rightarrow e^- \mu^+ \mu^- Z$

As was previously discussed, to estimate additional uncertainty in the $A'$ yield prediction, the cross-check between a clean sample of $\approx 5 \times 10^5$ observed and MC predicted $\mu^+ \mu^-$ events from the reaction

$$e^- Z \rightarrow e^- Z\gamma; \gamma \rightarrow \mu^+ \mu^-$$ (4.1)

with the energy deposition $E_{\text{ECAL}} \lesssim 60 \text{ GeV}$ was made. The number of $A'$ and dimuon events are both proportional to the square of the Pb nuclear form factor $F(q^2)$ and are sensitive to its shape. As the mass ($m_{A'} \approx m_\mu$) and $q^2$ ($q \approx m_{A'}/E_{A'} \approx m_\mu/E_\mu$) ranges for both reactions are similar, the observed difference can be interpreted as due to the accuracy of the dimuon yield calculation for heavy nuclei and, thus can be conservatively accounted for as additional systematic uncertainty in $n_{A'}(\epsilon, m_{A'}, \Delta E_{A'})$. In that way, the performance of NA64 was monitored
online, and the sensitivity of the experiment was gauged by recording the number of dimuon events reconstructed online from the two-muon trigger. These events were from reaction (4.1) in which high-energy bremsstrahlung photon converted in the reaction $\gamma Z \rightarrow \mu^+\mu^-$ to two muons. The overall probability to produce dimuon pair in this way with $E_{ECAL} \lesssim 60$ GeV is $\lesssim 10^{-5}$. During the NA64 running, over $10^5$ of these events were reconstructed using loose cuts on the presence of muon in the HCAL. The production mechanisms of the $A'$ and $\mu^+\mu^-$ pair is different, however there are some similarities the cross section in both cases is $\simeq F(q^2)$, the final state has the mass in the same (sub-GeV) mass range.

4.1 Dimuon Events simulation and selection

We are beginning detailed comparisons of data and Monte Carlo to evaluate the detector acceptance for dimuon events from reaction (4.1) in the ECAL target. For the dimuon production we have relied on two codes, GEANT4 [21] and specially developed code by NA64 [10], which was also used for simulation of dark photon production. In this Section, we report our comparison with data mostly on GEANT4 simulation for decays and propagation of muons through the detectors. However, we anticipate that comparison of dimuon results with the NA64 code will follow in the near future, as it expected to be an important cross-check of the $A'$ yield calculations of Ref.[10].

The selection of incoming electrons was performed using the synchrotron radiation detectors (SRD). The selection of events with energy deposition in the active ECAL target significantly smaller than the beam energy was partly performed by the trigger in the physical runs. The trigger accepted only events with the calibrated energy deposition smaller than $\simeq 85$ GeV for the 100 GeV incoming electron beam. For more reliable selection a stricter cut was applied in the offline selection, as described below. Further selection of dimuon events was performed mainly using the energy deposition in the HCAL modules. Due to the fact, that essentially only muons can punch through the total length of 14-21 $\lambda_{int}$ of HCAL modules 1-3, while the hadrons are absorbed in the HCAL module 1, this rejects events from beam hadrons and lower energy electrons that accidentally pass the electron identification and events with gamma-nuclear and electron-nuclear interactions in the active target. The dimuon peak in module 2 for the data and MC is shown in Fig.32 (see below for the selection cuts and normalization). The following cuts were used for the selection:

- energy deposited in the ECAL $E_{ECAL} < 60 GeV$
- energy deposited in the HCAL modules: $2.5 < E_{HCAL1} < 6.25$ GeV, and $2. < E_{HCAL3} < 6.25$ GeV
The upper cut on the energy in HCAL1 and HCAL3 modules for the data was increased to 6.35 GeV in order to take into account the difference in the energy resolution (it is worse in data) and pileup effects.

![Energy distribution in ECAL](image)

**Figure 32.** Dimuon peaks in the HCAL module 2 (left panel) and HCAL module 3 (right panel) for the selected dimuons from the data (points) and MC (histogram).

### 4.2 Dimuon yield evaluation

The production yield of dimuons was estimated from the number of reconstructed dimuon events and estimated with the following equation

\[ n_{2\mu} = \sigma_{\text{eff}} \epsilon_{T\gamma} \epsilon_{\text{HCAL}} \]  

(4.2)

The energy in the ECAL for the low intensity run 2351 and correspondingly normalized MC is shown in Fig. 2. In the normalization the inefficiency of trigger counters and SRD not simulated in MC, total value of 0.8, is taken into account. Some muons don’t reach the HCAL module 3, for this reason the small peak from one muon appears in it as can be seen in Fig.32(right pannel). For higher intensity runs an additional inefficiency because of pileup appears. The ECAL energy distribution is not distorted, see Fig.33. The dependency of dimuon selection efficiency on intensity is summarized in Table 3. Note that the run 2443 had a ECAL preshower included in trigger (threshold 0.5 GeV). This is taken into account in the MC prediction, however the simulation shows that the effect is very small (4 events out of 700 are lost).

### 4.3 ECAL energy distributions

Additional cross-check can be made by comparing distributions of the energy \( E_{\text{ECAL}}^{\mu} \) deposited by scattered electrons from the reaction (4.1) in the ECAL taking into
Table 3. Dimuon selection efficiency for the runs with different beam intensity. The numbers in brackets in the last row are from the MC estimate with pileup smearing in ECAL.

<table>
<thead>
<tr>
<th>Run</th>
<th>beam intensity, $10^3 n_{ev}$</th>
<th>$n_{\text{ev}}$, $10^6$</th>
<th>$n_{MC}$</th>
<th>$n_{data}$</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2351</td>
<td>1780</td>
<td>171</td>
<td>1223</td>
<td>957</td>
<td>0.8</td>
</tr>
<tr>
<td>2359</td>
<td>3170</td>
<td>208.5</td>
<td>1491</td>
<td>1056</td>
<td>0.71</td>
</tr>
<tr>
<td>2443</td>
<td>4600</td>
<td>597</td>
<td>4271 (3545)</td>
<td>2279</td>
<td>0.53 (0.64)</td>
</tr>
</tbody>
</table>

Figure 33. Distribution of energy deposited in the ECAL target by the scattered electron from the reaction (4.1) for low (run2351, left panel) and medium (run2359, right panel) intensity runs for the selected dimuons events from the data (points) and MC (histogram).

account small corrections due to dimuon energy depositions. In Fig. 33 the distributions of the energy $E^{\mu}_{\text{ECAL}}$ obtained from runs with different beam intensity is shown. One can see that the predicted and measured spectra are in a reasonable agreement.

5 Continuation of the ongoing program in 2017 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 $A' \rightarrow \text{invisible}$ 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 larger 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.

### 5.1 Search for the $A' \to \text{invisible decays}$

The successful run in October 2016 with two-spill structure during 48 sec cycle time and intensity $\gtrsim 5 \times 10^6 \text{ EOT/spill}$ gave us a five-times increase in the $A'$ yield. An extrapolation from this run shows that we can collect $\gtrsim 3 \times 10^{12} \text{ EOT}$ in $\approx 6$ months of running. The combined 2016-2017-2018 and 2021-24 data sample will include more than $(2 - 3) \times 10^{12} \text{ EOT}$ resulting in a significant coverage of the $(\epsilon; m_{A'})$ parameter space up to $\epsilon \lesssim 10^6; m_{A'} \lesssim 1 \text{ GeV}$.

### 5.2 Search for a new light $X$ boson from the $^8\text{Be}$ excess

The experiment of Krasznahorkay et al. [30] in ATOMKI has reported observation of a $6.8 \sigma$ excess of events in the invariant mass distributions of $e^+e^-$ pairs produced in the $^8\text{Be}^*$ 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 [31, 32] 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 $M_X = 16.7 \text{ MeV}$. 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.

All this makes the search for such $X \to e^+e^-$ decay mode quite interesting and exciting. Below we show that NA64 is able to cover a significant region of the predicted parameter space, see Fig.46 from Ref.[31, 32].

#### 5.2.1 The search method

The method to search for the $X$ is the following [6, 7]. If it exists, the bremsstrahlung $X$ could be produced through the reaction

$$e^- + Z \to e^- + Z + X; \; X \to e^+e^-$$  \hspace{1cm} (5.1)

of a high-energy electron scattering off nuclei in the compact tungsten-scintillator electromagnetic calorimeter (WCAL). The reaction (5.1) typically occurs within the first few radiation length ($X_0$) of the WCAL detector. The bremsstrahlung $X$ propagates without interpretation nd decays in flight into an $e^+e^-$ pair. The detectable signal events are those in which the $X$ decays downstream the WCAL and the veto counter V2 in the decay volume, see Fig.34. A fraction of the primary beam energy $E_1 = E_0 - E_X$ is deposited in the WCAL. The WCAL’s downstream part is served as a dump to absorb completely the e-m shower tail. For the radiation length $\lesssim 1 \text{ cm},$
Figure 34. Schematic illustration of the NA64 setup to search for $X \rightarrow e^+e^-$ decays with 100 GeV $e^-$ at the H4 beamline. The incident 100 GeV electron energy absorption in the WCAL is accompanied by the emission of bremsstrahlung Xs in the reaction $eZ \rightarrow eZX$ of electron scattering off W nuclei. The part of the primary beam energy is deposited in the WCAL by the recoil electron, while the rest of the total energy is transmitted by the X through the WCAL. The X penetrates the WCAL and veto V2 without interactions and decays in flight into a narrow $e^+e^-$ pair, which generates the second electromagnetic shower in the ECAL resulting in the two-shower signature in the NA64 detector. The sum of energies deposited in the WCAL and ECAL is equal to the primary beam energy. The detector is additionally equipped with the massive hadronic calorimeter (HCAL) to enhance its hermeticity.

and the total thickness of the WCAL $\simeq 30 \, X_0$ (rad. lengths) the energy leak from the WCAL into the V2 is negligibly small. The energy $E_X$ is transmitted thorough the “WCAL wall” by the X, and deposited in the second downstream calorimeter ECAL by the $e^+e^-$ pair from the X decay, as shown in Fig. 34. 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.

5.2.2 Test run

In October 2016 a short run to test feasibility for the $X \rightarrow e^+e^-$ decays search was taken. The NA64 detector configuration shown in Fig. 34 employs the 100 GeV $e^-$ beam from the H4 beam line. Upstream of the SRD the detector was identical to that used for the $A' \rightarrow invisible$ decay search. Downstream the SRD, the NA64 detector configuration shown in Fig. 34 differed from that used for the $A' \rightarrow invisible$ 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 $e^- Z \rightarrow e^- ZX$ 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 sand-
wich 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 $X \rightarrow e^+e^-$ decays produced in $e^-Z$ interactions 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. 34, above those expected from the background sources. The signal candidate events have the signature:

$$S_X = \Pi S_i \times \text{WCAL} \times \text{V2} \times \text{ECAL} \times \text{V2} \times \text{V3} \times \text{HCAL},$$

(5.2)

and should satisfy the following selection criteria:

- The starting point of (e-m) showers in the WCAL and ECAL should be localized within few first $X_0$s.
- The lateral and longitudinal shapes of both showers in the WCAL and ECAL are consistent with an electromagnetic one. The fraction of the total energy deposition in the WCAL is $f \lesssim 0.1$, while in the ECAL it is $(1 - f) \gtrsim 0.9$ (see energy spectra in Fig. 41, and discussion below).
- No energy deposition in the V2 and V2.
- The signal (number of photoelectrons) in the decay counters S1 and S2 is consistent with the one expected from two minimum ionizing particle (mip) tracks. At low beam energies, $E_0 \lesssim 30$ GeV, two isolated hits in each counter are requested.
- The sum of energies deposited in the WCAL+ECAL is equal to the primary energy, $E_1 + E_2 = E_0$.

The tungsten - scintillator calorimeter One of the main requirement for the sensitive search for the $X \rightarrow e^+e^-$ decay in the still unexplored parameter space, is to achieve a highly compact design, having a small Moliere radius and as short radiation length as possible. Thus, the calorimeter has to be a tungsten calorimeter. The total length of the detector should be $\lesssim 30$ cm. This implies having the greatest amount of absorber possible, consistent with obtaining the required energy resolution. The
Figure 35. Schematic illustration of a scintillator-fiber-tungsten module consisting of a stack of 3 mm thick tungsten and 2 mm thick scintillator plates. Wavelength shifting fibers pass laterally through the plates and are read out with a photomultiplier.

energy resolution should be $\Delta E/E \approx 15\% / \sqrt{E}$. It should be possible to measure the longitudinal shower shape, and the $e/\pi$ rejection should be $\lesssim 10^{-3}$. Timing properties should allow stable running at the beam rate $\approx 2$ MHz. The radiation hardness must be better than 1000 Gy. The energy resolution of the WCAL calorimeter as a function of the beam energy was measured to be $\sigma_E = \frac{15\%}{\sqrt{E}} \oplus 3\% \oplus \frac{142 \text{ MeV}}{E}$.

To fulfill these design requirements, we adopted a tungsten scintillator sandwich configuration, as shown in Fig. 35. It consists of a standard sandwich arrangement of alternating W absorber and scintillator plates read out with wavelength shifting fibers running laterally through each scintillator plate. Our WCAL module design has high density and represents a compact calorimeter with a small overall module size (roughly 10 square Moliere radius at the front). To improve the $e/\pi$ rejection factor the WCAL with the longitudinal segmentation is designed. One possible option of the calorimeter segmentation is shown in Fig. 35. This design would have the advantage of readout longitudinal shower profile, by grouping fibers from the first $\approx 4 - 5$ $X_0$ radiation lengths into a separate preshower detector. The WCAL is $\approx 100 \times 100$ mm$^2$ in cross section and about 200 mm ($\approx 30$ $X_0$) long, see Fig. 35. Timing and energy deposition information from each plate has been digitized for each event. In Fig. 36 the photograph of the WCAL calorimeter located at the H4 beam during test run in October 2016 is shown.

To evaluate the basic performance of this design we have carried out a Monte Carlo study by using GEANT4 [21]. For the calorimeter design, the energy resolution requirements are quite stringent and are in the range of a few % for the energy region 30-100 GeV. We studied the WCAL energy resolution for various tungsten plate thicknesses keeping the scintillator thickness constant at 3.0 mm. Fig. 37
Figure 36. Photograph of the WCAL calorimeter at the H4 beam during the test run in October 2016.

gives the results of these simulations. The curves were fit to a parametrization $\Delta E/E = a/\sqrt{E} + b$ and the results of the fits for the selected W plate thickness of 3.5 mm is $a = 0.15$ and $b = 0.004$. It shows that an energy resolution $\sim 15\%/\sqrt{E}$ can be achieved with the selected sampling. Note, that only sampling fluctuations and leakage were included in this simulation, therefore the photo-statistics contribution has to be kept small compared to this value.

We also studied the Moliere radius of this design. The fraction of the energy of a shower contained within a given radius (in terms of radiation length) for a calorimeter with one radiation length sampling and 3 mm scintillator was simulated. For pure tungsten, the Moliere radius is $R_M \simeq 2.6 \ X_0 \simeq 9.3$ mm, and is the radius that contains approximately 90% of the shower energy. From the simplified simulation, we can see that in order to absorb nearly 90% of the energy in the counter, its lateral size should be still within roughly one $R_M$. It was also found that this value is nearly independent of energy from 1-40 GeV. The Moliere radius of this configuration is almost the same as that of pure tungsten, it is larger by about 20%.

The WCAL calorimeter is followed by the veto counter V2. The veto counter was 10 mm thick made of plastic scintillator with a high light yield of $\sim 10^2$ photoelectrons per 1 MeV of deposited energy. In the design and construction of this counter the main focus was to maximize the V2 detection efficiency. The typical veto’s inefficiency measured for the MIP detection was, conservatively, $\lesssim 10^{-4}$. The main task of the counter is to measure precisely the time and energy deposition of particles escaping the WCAL from the back surface in order to allow the matching with the...
Figure 37. Simulated energy resolution (FWHM) as a function of the incident energy for a calorimeter module configuration shown in Fig. 35 for different absorber plate thicknesses, indicated near the curves. The scintillator plate thickness was kept constant at 3.0 mm for each configuration. Only contributions from sampling fluctuations and energy leakage are included.

real electron event and to reject background from hadronic and pile-up events. In Fig. 38 expected distributions of energy deposited in the V2 from the interactions induced by the 100 GeV $e^-$’s in the WCAL target obtained with simulations and measured in the October run are shown. The difference in distributions, attributed mainly to the difficulties in simulations of the pileup effects at high beam intensities, is taken into account as an additional contribution to the systematic errors for the V2 efficiency to the signal events.

5.2.3 Simulation of the $X$ and dark photon production

The production of $X$ boson off nuclei, which is the signal that we search for, was performed by the code described in Ref.[10], compiled as a part of the Geant4 application. We assumed that both electrons and positrons of the electromagnetic shower initiated by the beam electron in the tungsten calorimeter WCAL can produce $X$ with the same cross section. For the visible mode configuration the subsequent
**Figure 38.** Distributions of energy deposited in the V2 counter from the interactions induced by the 100 GeV $e^-$’s in the WCAL target and obtained with simulations (histogram) and measured in the October run data (crosses). 1 MIP $\approx$ 2 MeV deposited energy.

**Figure 39.** Distribution of simulated signal events on the ($E_{WCAL}, E_{ECAL}$) plane.

$X \rightarrow e^+e^-$ decay was simulated. The resulting electron - positron pair was traced by Geant4 in the same way as all other particles. The life time of X depends on its mass and on the mixing constant $\epsilon_e$. We used the mass $m_X = 16.7$ MeV and coupling $\epsilon_e \approx 10^{-3}$ as a reference point. Choosing cuts for the signal selection was performed in the following way. It turned out that the veto counter VTWC was wider than needed. Due to particles exiting through the sides of WCAL, for the V2 cut less than one MIP ($\approx$2 MeV deposited energy, see Fig.38) the efficiency to signal dropped significantly. So the lower cut at approximately 1.3 MIP was chosen. The upper cut at the same value was chosen for S4, selecting events with at least two charged particles before the ECAL. Distribution of simulated signal events in
the \((E_{WCAL}; E_{ECAL})\) plane is shown in Fig.39. The distribution of the total energy deposited in WCAL and ECAL is shown in Fig.40. This total energy deposition is the main variable for the signal selection. Two additional criteria were used.

The yield of the \(X\) as a function of the WCAL thickness for different values of the threshold on \(V2\) signal is shown in Table4.

**Table 4. Yield of the \(X\) boson from the W-target**

<table>
<thead>
<tr>
<th>item</th>
<th>no cut on (E_{V2})</th>
<th>(E_{V2} &lt; 1.3) MIP</th>
<th>(E_{V2} &lt; 0.7) MIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Run Oct’16</td>
<td>712</td>
<td>458.6</td>
<td>358</td>
</tr>
<tr>
<td>2. Run Oct’16, no gaps, V2 of WCAL size</td>
<td>735</td>
<td>534.7</td>
<td>422</td>
</tr>
<tr>
<td>3. 2.+ 5 layers</td>
<td>663</td>
<td>587.2</td>
<td>528</td>
</tr>
<tr>
<td>4. 3.+5layers</td>
<td>547</td>
<td>500</td>
<td>477</td>
</tr>
</tbody>
</table>

One can notice that for cases \(E_{V2} < 1.3\) MIP and \(E_{V2} < 0.7\) MIP the \(X\)-yield for the configuration 3) is higher than that of 2), in spite of the less thickness of the latter. The possible explanation is that the yield is proportional to the product \(P(t) \times P(V2)\) of probability for \(X\) to escape WCAL and probability for the leak energy to be below \(V2\) threshold. So the product has maximum for the WCAL thickness around \(t \simeq 35\ X_0\).
5.2.4 Data sample and selection criteria

In October run 2016 a short run was taken in order to study the feasibility of the search for the \( X \rightarrow e^+e^- \) decay in NA64. For this run the detector shown in Fig.34 was assembled including the two magnet option, which was used for better primary electron identification with the PbSc SRD detector. The following number of eot:

\[
\begin{align*}
\text{• } n_{\text{eot}} &\approx 0.5 \cdot 10^9 \text{ eot with intensity } \approx 2 \cdot 10^6 \text{e-} / \text{spill.} \\
\text{• } n_{\text{eot}} &\approx 1.8 \cdot 10^9 \text{ eot with intensity } \approx 3 \cdot 10^6 \text{e-} / \text{spill.} \\
\text{• } n_{\text{eot}} &\approx 3 \cdot 10^9 \text{ eot with intensity } \approx 5 \cdot 10^6 \text{e-} / \text{spill.}
\end{align*}
\]

were recorded. Currently, the development of the improved version of the reconstruction and analysis program is in progress, as well as the study of systematic effects, background sources for the final detector configuration in 2017. Preliminary results looks promising and can also play an essential role in helping us plan for a future searches of the \( A' \rightarrow e^+e^- \) decays at H4 line.

The initial sample for the selection of \( e^+e^- \) candidates was obtained from the events satisfying the WCAL trigger (5.2). We used for analysis all available data from October run 2016. There are several steps in event selection.

At the first step of the analysis with a simple filter we selected events with the following properties:

\[
\begin{align*}
\text{• } &\text{the usual quality cuts: bad runs, unused hits, etc...should be satisfied.} \\
\text{• } &\text{event should have one good quality track at the entrance, with the number of hits not more than 2 per each MM plane.} \\
\text{• } &\text{the selected events were also required to be in time with the trigger scintillator counters.} \\
\text{• } &\text{No MIP signals in V2 and V3. Since the energy deposited in the veto played a crucial role in the analysis, only events with the energy deposition as listed in Table 4 were accepted.} \\
\text{• } &\text{no activity in HCAL modules.}
\end{align*}
\]

The purpose of these cuts is to clean up the initial sample.

In measurements with the H4 beam, it turned out that the veto counter V2 was wider than needed. Due to particles exiting through the sides of WCAL, for the V2 cut less than one MIP the efficiency to signal dropped significantly. So the lower cut at approximately \( \approx 1.3 \) MIP was chosen. The upper cut at the same value was chosen for S4, selecting events with at least two charged particles before the ECAL. Finally the \( X \rightarrow e^+e^- \) candidate events were selected with the following criteria:
(i) no requirement of an oppositely charged particles in the pair or presence of a track identified as positron, i.e. the behavior of the \( e^+e^- \) tracks with a narrow angle must be consistent with the one expected from a single electron track.

(ii) the starting point of (e-m) showers in the ECAL should be localized within a few first \( X_0 \)s. the lateral and longitudinal shapes of the ECAL shower is consistent with the electromagnetic one. ECAL shower shape generated by the decay \( e^+e^- \) pair should satisfy \( \chi^2 < 8 \)

(iii) energy in the hadronic calorimeter < 0.4 GeV. This cut serves as HCAL veto and was cross-checked with the random trigger and Monte Carlo studies.

(iv) Muon HCAL veto: no muons in the final state.

(v) The fraction of the total energy deposition in the WCAL is \( f \lesssim 0.7 \), while in the ECAL it is \((1 - f) \gtrsim 0.3 \) (see Fig. 41 and discussion below).

(vi) no energy deposition in the V2 (<1.5 MIP) and V3(< 0.5 MIP).

(vii) the signal (number of photoelectrons) in the decay counter S4 is consistent with the one expected from two MIP tracks: \( S4 > 1.5 \) MIP. For low energies of the \( e^+e^- \) pairs with \( E_{e^+e^-} \lesssim 30 \) GeV two isolated hits in the M3,M4 could be requested (to be studied).

(viii) the sum of energies deposited in the WCAL and ECAL is equal to the primary energy, \( E_{WCA} + E_{ECA} = E_0 \) within the energy resolution for events with maximum energy deposited in the cell (3;3) of the ECAL.

In total out of about \( 2.6 \times 10^6 \) events recorded, see Table 2, only 16 events passed above search criteria, and no candidate events satisfying \( E_{WCA} + E_{ECA} > 92 \) GeV requirement were found. The evolution of selection efficiency is shown in Table 5.

### 5.2.5 Results from the test run

The distribution of the selected candidate events on the in the \( (E_{WCA}, E_{ECA}) \) plane from the October 2016 run is shown in Fig. 42. The dashed band shows the signal box region corresponding to \( E_{WCA} + E_{ECA} = E_0 \). The distribution of the total energy deposited in WCAL and ECAL is shown in Fig. 43. This distribution can be compared with the one shown in Fig. 44, where the distribution of energy deposited in the WCAL by 100 GeV \( e^- \) is shown. This plot was used to determine roughly the size of the signal box \( 90 \lesssim E_{tot} \lesssim 110 \) GeV. Note, that the total energy deposition \( E_{tot} \) is the main variable for the signal selection. Two additional criteria were used for the signal selection. The first is the requirement that the ECAL cell with the maximal energy deposition is the cell (3,3), the cell where the beam enters the ECAL when WCAL is not installed. The signal simulation showed that the efficiency of this
Figure 41. The $X$ emission spectrum from 100 GeV electron beam interactions in the Pb target calculated for $m_X = 10$ MeV and $m_X = 500$ MeV. The spectra are normalized to about the same number of events.

Table 5. Efficiency for the $X \rightarrow e^+ e^-$ decay event selection in simulations and data. Also flow of the numbers for the single electron selection is shown.

<table>
<thead>
<tr>
<th>item</th>
<th>Simulations $m_X = 16.7$ MeV</th>
<th>Data</th>
<th>Single $e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n_{acc}$ signal</td>
<td>$n_{acc}$ candidates</td>
<td>$n_{acc}$ candidates</td>
</tr>
<tr>
<td>Initial number of events</td>
<td></td>
<td>2.6 $\times$ 10$^6$</td>
<td>10$^5$</td>
</tr>
<tr>
<td>Trigger WCAL $\lesssim$ 70 GeV</td>
<td>1720</td>
<td>2.5 $\times$ 10$^6$</td>
<td>16</td>
</tr>
<tr>
<td>Veto V2 cut $&lt; 1.3$ MIP</td>
<td>1132</td>
<td>8.5 $\times$ 10$^5$</td>
<td>1</td>
</tr>
<tr>
<td>Veto V3 &lt; 1.4 MIP</td>
<td>1131</td>
<td>6.3 $\times$ 10$^5$</td>
<td>0</td>
</tr>
<tr>
<td>ECAL max in cell (3,3)</td>
<td>1065</td>
<td>4 $\times$ 10$^3$</td>
<td>16</td>
</tr>
<tr>
<td>ECAL shower shape, $\chi^2$</td>
<td>not used</td>
<td>not used</td>
<td>not used</td>
</tr>
<tr>
<td>$E_{WCAL} + E_{ECAL} &gt; 92$ GeV</td>
<td>1062</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

requirement for the signal is higher than 99%. The second requirement is of no energy ($<0.8$ MIP) in VETO, it ensures that there are no hadrons after the WCAL.

We observe no events which pass our search criteria and selection cuts. The number of expected background events are approximately 0.3. The largest contribution to the background is expected either from the high-energy punch-tough photons or from the hadronic interactions with large $\pi^0$ component and the little charged
**Figure 42.** Selected event distribution on the \((E_{W\text{CAL}}, E_{E\text{CAL}})\) plane from the October 2016 run. The band shows the signal box region corresponding to \(E_{W\text{CAL}} + E_{E\text{CAL}} = E_0\).

**Figure 43.** Selected event distribution in the \(E_{\text{tot}} = E_{W\text{CAL}} + E_{E\text{CAL}}\) from the October 2016 run. The signal box region corresponding to \(90 \lesssim E_{\text{tot}} \lesssim 110\) GeV.

hadron activity.

After application of all these cuts - no \(e^+e^-\) candidates remained. In Fig. 42 the remaining event distribution in the \((E_{W\text{CAL}}, E_{E\text{CAL}})\) plane from the October run 2016. is presented. It is seen that after the application of all cuts no \(e^+e^-\) candidates events are left in the data in the signal band \(E_0 = E_{W\text{CAL}} + E_{E\text{CAL}}\). The 1D-distribution of variable \(E_{\text{tot}} = E_{W\text{CAL}} + E_{E\text{CAL}}\) is shown also in Fig.43. Background events 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 no candidate events left in the \(X \rightarrow e^+e^-\) signal region \(90 \lesssim E_{\text{tot}} \lesssim 110\) GeV which was approximately defined from the plot of Fig.44. The 90% C.L. upper limit for the production of the \(X\) can be calculated by using the following relation:

\[
N_{X \rightarrow e^+e^-} < N_{X \rightarrow e^+e^-}^{90\%} \tag{5.3}
\]
Figure 44. Distribution of energy deposited in the WCAL by 100 GeV $e^-$ from the October run 2016. The signal box region is determined roughly to be $90 \lesssim E_{\text{tot}} \lesssim 110$ GeV.

where $N_{X \rightarrow e^+e^-}^{90\%}$ is the 90% C.L. upper limit for the expected number of signal events, calculated according to ref. [10].

5.2.6 Background

The largest contribution to the background is expected mainly from i) high-energy punch-through photons from the first, second e-m shower generations; ii) single $\pi^0$ production in the charge-exchange reactions of beam pions at the last W plates of the WCAL calorimeter.

(i) $\gamma, e^-$ - punchthrough level and its direct measurements

- The leak of the primary electron energy into the ECAL, could be due to the bremsstrahlung process $e^- Z \rightarrow e^- Z \gamma$, when the emitted photon carries away almost all initial energy, while the final state electron with the much lower energy $E_{e^-} \simeq 0.1E_0$ is absorbed in the WCAL. The bremsstrahlung photon could punch through the WCAL and V2 without interactions, and produce an $e^+e^-$ pair in the S1, which deposit all its energy in the ECAL. The photon could also be absorbed in a photonuclear reaction occurring in the WCAL and resulting in, e.g. an energetic leading secondary neutron. In the first case, to suppress this background, one has to use the WCAL of enough thickness, and as low veto energy threshold as possible. Assuming that the primary interaction vertex is selected to be within a few first $X_0$s, for the total remaining WCAL+V2 thickness of $\simeq 30 \ X_0$, the probability for a photon to punch through both WCAL and V2 without interaction is conservatively $P_{\text{pth}} < 10^{-10}$. Thus, this background is at the negligible level. In the second case, an estimation results in a similar background level $< 10^{-10}$. 
Figure 45. Selected "neutral trigger" event distribution in the \((E_{W\text{CAL}}; E_{E\text{CAL}})\) plane from the October run 2016. The yellow band shows the signal box region corresponding to \(E_{W\text{CAL}} + E_{E\text{CAL}} = E_0\).

- Punch-through primary electrons, which penetrate the WCAL and V2 without depositing much energy could produce a fake signal event. It is found that this is also an extremely rare event.

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, were studied. In Fig.45 the selected event distribution in the \((E_{W\text{CAL}}; E_{E\text{CAL}})\) plane from the October run 2016 is shown. No events are observed in the signal region indicated with a yellow band corresponding to the condition \(E_0 = E_{W\text{CAL}} + E_{E\text{CAL}}\). This allows to set a 90% C.L. upper limit \(P_{\text{pth}} < 10^{-9}/\text{eot}\) on the probability to observed a single punch-through event with energy \(E'_{\text{pth}} \gtrsim 50\ \text{GeV}\) per eot, which is consistent with the above considerations.

(ii) Hadronic background

The hadronic beam-related background can be due to a beam particle misidentified as an electron. This background is caused by some pion, proton and muon contamination in the electron beam. One could perform independent direct measurements of its level with the same setup by using pion and muon beams of proper energies. For this purpose the primary beam is tuned to pions. The muons can be selected by putting thick absorber on the primary beam line.

- The first source of this type of background could be due to the

\[
p(\pi) + A \rightarrow n + \pi^0 + X, \ n \rightarrow \text{ECAL} \tag{5.4}
\]
reaction chain: i) an incident hadron produces a neutral pion with the energy $E_{\pi^0} \lesssim 0.1E_0$ and an energetic leading neutral hadron, e.g. neutron, carrying the rest of the energy of the primary collision with the nucleus $(A,Z)$, ii) the neutral pion decays $\pi^0 \rightarrow 2\gamma$ generating an e-m shower in the WCAL, while iii) the neutron penetrates the rest of the WCAL and the veto counter V2 without interactions, scatters in the counter S1, producing low energy secondaries and deposits all its energy in the ECAL. The probability for such a reaction chain to occur can be estimated as

$$P_{p(\pi)} \simeq f_{p(\pi)} \cdot P_{\pi^0 n} \cdot P_{S1} \cdot P_n,$$  


where $f_{p(\pi)}$, $P_{\pi^0 n}$, $P_{S1}$, $P_n$ are, respectively, the level of the admixture of hadrons in the primary beam, $P_{p(\pi)} \lesssim 10^{-2}$, the probability for an incoming hadron to produce the $\pi^0 n$ pair in the WCAL, $P_{\pi^0 n} \simeq 10^{-4}$, the probability for the neutron to interact in S1, $P_{S1} \simeq 10^{-3}$, and the probability for the leading $n$ to deposit all its energy in the ECAL, $P_n \simeq 10^{-3}$. This results in $P \lesssim 10^{-12}$. The probability for neutral hadrons to interact in the S1 of thickness $\simeq 1$ mm, or $\simeq 10^{-3}$ nuclear interaction length, can be reduced significantly, down to $P_{S1} \simeq 10^{-4}$, by replacing it, e.g. with a wire chamber counter. This leads to $P \lesssim 10^{-13}$. At low energies $E_0 \lesssim 30$ GeV, the requirement to have two hits in the S1 would suppress the background further.

Note, that the cross section for the reaction $p(\pi) + A \rightarrow \pi^0 + n + X$, with the leading neutron in the final state, has not yet been studied in detail for the wide class of nuclei and full range of hadron energies. To perform an estimate of the $P_{\pi^0 n}$ value, we use data from the ISR experiment at CERN, which studied leading neutron production in $pp$ collisions at $\sqrt{s}$ in the range from 20 to 60 GeV [? ? ]. For these energies the invariant cross sections, obtained as a function of $x_F$ (Feynman $x$) and $p_T$, were found to be in the range $0.1 \lesssim E\frac{d\sigma}{dx_p} \lesssim 10$ mb/GeV$^2$ for $0.9 \lesssim x_F \lesssim 1$ and $0 \lesssim p_T \lesssim 0.6$ GeV [? ? ]. Taking these results into account, the cross sections for leading neutron production in our energy range are estimated by using the Bourquin-Gaillard formula, which gives the parametrized form of the invaria nt cross section for the production in high-energy hadronic collisions of different hadrons over the full phase-space, for more details see, e.g. [24]. The leading neutron production cross sections in $p(\pi) A$ collisions are evaluated from its linear extrapolation to the target atomic number.

In another case, the leading neutron could interact in a very downstream part of the veto counter producing leading $\pi^0$ without being detected. The $\pi^0$ decays subsequently into $2\gamma$ or $e^+ e^- \gamma$. The background from this events chain is also estimated to be very small.
• The fake signature $S_X$ arises when the incoming pion produces in a very upstream part of the WCAL a low energy neutral pion, escapes detection in the V2 counter due to its inefficiency, and either deposits all its energy in the ECAL, or decays in flight in the DV into an $e\nu$ pair with the subsequent decay electron energy deposition in the ECAL. In the first case, also relevant to protons, an analysis similar to the previous one, shows that this background is expected to be at the level $\lesssim 10^{-13}$. In the second case, taking into account the probability for the $\pi \rightarrow e\nu$ decay in flight, and that the electron would typically have about one half of the pion energy, results in a suppression of this background to the level $< 10^{-15}$.

The overall probability of the fake signal produced by an incoming hadron is estimated to be $P_{\mu(\pi)} \lesssim 10^{-13}$ per incoming electron. Another type of background is caused by the muon contamination in the beam.

(iii) Muon background

• The muon could produce a low energy bremsstrahlung photon in the WCAL, which would be absorbed in the detector, then penetrates the V2 without being detected, and after producing signals in the S1 and S2 counters, deposit all its energy in the ECAL through the emission of a hard photon:

$$\mu + Z \rightarrow \gamma + \mu + Z, \mu \rightarrow \text{ECAL}. \tag{5.6}$$

The probability for the chain (5.6) is estimated to be $P \lesssim 10^{-14}$. Similar to (5.4), this estimate is obtained assuming that the muon contamination in the beam is $\lesssim 10^{-2}$, the probability for the muon to cross the V2 counter without being detected is $\lesssim 10^{-4}$, and the probability for the $\mu$ to deposited all its energy in the ECAL is $\lesssim 10^{-7}$. Here, it is also taken into account that the muon should stop in the ECAL calorimeter completely to avoid being detected in the counter V2. An additional suppression factor arises from the requirement to have two-mip's signal in the decay counters.

• One more background source can be due the event chain

$$\mu + Z \rightarrow \mu + \gamma + Z, \mu \rightarrow e\nu\nu, \tag{5.7}$$

when the incoming muon produces in the initial WCAL part a low energy bremsstrahlung photon, escapes detection in the counter V2, and then decays in flight in the DV into $e\nu\nu$. There are several suppression factors for this background: i) the relatively long muon lifetime resulting in a small probability to decay, ii) the presence of two neutrinos in the $\mu$ decay. The energy deposition of decay electrons in the ECAL is typically significantly smaller than the primary energy $E_0$, and iii) the requirement to have
Table 6. Expected contributions from different background sources estimated for the beam energy 100 GeV (see text for details).

<table>
<thead>
<tr>
<th>Source of background</th>
<th>Expected level</th>
</tr>
</thead>
<tbody>
<tr>
<td>punchthrough γs</td>
<td>&lt; $10^{-10}$</td>
</tr>
<tr>
<td>hadronic reactions</td>
<td>$\lesssim 2 \times 10^{-13}$</td>
</tr>
<tr>
<td>µ reactions</td>
<td>$\lesssim 10^{-14}$</td>
</tr>
<tr>
<td>accidentals</td>
<td>$\lesssim 10^{-14}$</td>
</tr>
<tr>
<td>Total (conservatively)</td>
<td>$&lt; 10^{-10}$</td>
</tr>
</tbody>
</table>

double mip energy deposition in the beam counters S1 and S2. All these factors lead to the expectation for this background level to be at least $\lesssim 10^{-14}$.

- A random superposition of uncorrelated events during the detector gate time could also result in a fake signal. Taking into account the selection criteria of signal events results in a small number of these background events $\lesssim 10^{-14}$.

The overall probability of the fake signal from muons is estimated to be $P_\mu \lesssim 10^{-14}$ per incoming electron, and the accidental background is below $\lesssim 10^{-14}$.

In Table 6 contributions from all background sources are summarized for the beam energy of 100 GeV. 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.

5.2.7 Sensitivity of the experiment

To estimate the sensitivity of the proposed experiment a simplified feasibility study based on GEANT4 [21] Monte Carlo simulations has been performed for 30 and 150 GeV electrons. The energy threshold in the WCAL is taken to be 0.5 GeV. The reported further analysis also takes into account passive materials from the walls of the decay vessel.

The significance of the $A' \rightarrow e^+e^-$ decay discovery with the described detector scales as [25, 26]

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

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.
For a given number of electrons on the target of length $L'$, $n_e \cdot t$ (here, $n_e$ is the electron beam intensity and $t$ is the experiment running time) and $X$ flux $dn_X/dE_X$, the expected number of $X \rightarrow e^+e^-$ decays occurring within the fiducial volume of the DV with the subsequent energy deposition in the ECAL calorimeter, located at a distance $L$ from the $X$ production vertex is given by

$$n_X \sim n_e t \int A \frac{dn_X}{dE_X} \exp\left(-\frac{L/M_X}{p_X \tau_X}\right) \left[1 - \exp\left(-\frac{L M_X}{p_X \tau_X}\right)\right] \frac{\Gamma_{e^+e^-}}{\Gamma_{tot}} \varepsilon_{e^+e^-} dE_X dV,$$

(5.9)

where $p_X$ is the $X$ momentum, $\tau_X$ is the $X$ lifetime at the rest frame, $\Gamma_{e^+e^-}$, $\Gamma_{tot}$ are the partial and total $X$-decay widths, respectively, and $\varepsilon_{e^+e^-}$ ($\approx 0.9$) is the $e^+e^-$ pair reconstruction efficiency. The flux of $X$s produced in the process (5.1) is calculated by using the $X$ production cross section in the $e^-Z$ collisions from Ref. [? ]. The acceptance $A$ of the ECAL calorimeter is calculated tracing $X$s produced in the WCAL to the ECAL, and is close to 100%.

**Figure 46.** The $^8$Be signal region, along with current constraints and projected sensitivities of future experiments in the $(m_X : \varepsilon_e)$ plane as discussed in Ref.[31, 32]. The white points indicate expected 90% C.L. exclusion areas in the $(m_X; \varepsilon_e)$ 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 $2 \times 10^{-4} < |\varepsilon_e| < 1.4 \times 10^{-3}$, while the excluded area is $7 \times 10^{-5} < |\varepsilon_e| < 0.9 \times 10^{-3}$.

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. (5.8) and (5.9) and into account and using the relation $n_X(M_X) < n^{90\%}_X(M_X)$, where $n^{90\%}_X(M_X)$ 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 ($n^{90\%}(M_X) = 2.3$ events), the exclusion regions corresponding to accumulated statistics $10^{11}$ eot at 100 GeV are shown in Fig. 46. One can see, that these exclusion areas are complementary to the ones expected from the planned APEX (full run), HPS and DarkLight experiments, which are also shown for comparison [31, 32]. In Fig. 47, 48, the number of observed events from the $X \rightarrow e^+e^-$ decays as a function of coupling $\epsilon_e$ for different $e^-$ beam energies and accumulated number of events. In Fig. 48 the curves are obtained after parameterization of the $n_x$ vs $\epsilon_e$ dependence shown in Fig. 47 with the function

$$f(\epsilon_e) = \alpha \epsilon_e^2 \exp(-\beta \epsilon_e^2) \quad (5.10)$$

where the first term $\alpha \epsilon_e^2$ describes the $X$ yield from the reaction $eZ \rightarrow eZX$ in the WCAL, while the second term $\exp(-\beta \epsilon_e^2)$ corresponds to the fraction of $X$s decaying outside of the WCAL. The fit gives $\alpha \simeq 8 \times 10^8$, $\beta \simeq 6.7 \times 10^6$. In Fig. 48 the coupling $\epsilon_e$ range for $^8$Be excess is also shown. The horizontal line indicates the level of $n_X = 2.3$ events above which the values of the coupling $\epsilon_e$ are excluded in case of no signal observation.

**Figure 47.** The number $n_X$ of observed events from the $X \rightarrow e^+e^-$ decays as a function of coupling $\epsilon_e$ calculated for several values of the coupling $\epsilon_e$ indicated by red points. The horizontal line indicates the level of $n_X = 2.3$ events above which the values of the coupling $\epsilon_e$ are excluded in case of no signal observation.

The statistical limit on the sensitivity of the proposed experiment is proportional to $\epsilon_e^2$. Thus, it is important to accumulate a large number of events. As one can see from Eq. (5.9), the obtained exclusion regions are also sensitive to the choice of the length $L'$ of the calorimeter WCAL, which should be as short as possible. As discussed in Sec. 2.1, assuming the maximal secondary H4 beam rate $n_e \simeq 5 \times \ldots$
$10^6$ $e^-$/spill at $E_0 \simeq 100 - 150$ GeV, we anticipate $\simeq 10^{11}$ collected $e^-$s during $\simeq 2$ weeks of running time for the experiment. Note, that since the decay time of the scintillating-fiber light signal is $\tau \lesssim 50$ ns, the maximally allowed electron counting rate in order to avoid significant pileup effect is, roughly $\lesssim 1/\tau \simeq 10^7$ $e^-$/s. This is well compatible with the maximal beam rate during the 4.8 s spill, which is expected to be $\lesssim 10^7/4.8s \simeq 2 \times 10^6$. To minimize dead time, one could use a first-level trigger rejecting events with the ECAL energy deposition less than, say, the energy $\simeq 0.9E_0$ and, hence, run the experiment at a higher event rate.

**Figure 48.** The number of observed events from the $X \rightarrow e^+e^-$ decays as a function of coupling $\epsilon_e$ for different $e^-$ beam energies and accumulated number of events. The curves are obtained after parameterization of the $n_X$ vs $\epsilon_e$ dependence shown in Fig.47 The coupling $\epsilon_e$ range for $^8$Be excess is also shown. The horizontal line indicates the level of $n_X = 2.3$ events above which the values of the coupling $\epsilon_e$ are excluded in case of no signal observation.

In the case of the signal observation, to cross-check the result, one could remove the decay vessel DV and put the calorimeter ECAL behind the WCAL. This would not affect the main background sources and still allow the $X$'s production, but with their decays upstream of the ECAL calorimeter being suppressed. The distributions of the energy deposition in the WCAL and ECAL in this case would contain mainly background events, while the signal level from the decays $A' \rightarrow e^+e^-$ should be reduced. The background can also be independently studied with the muon and pion beams of the same energy. The evaluation of the $X$ mass value could be obtained
Table 7. Data-taking efficiency and live-time of NA64.

<table>
<thead>
<tr>
<th></th>
<th>NA64-2016</th>
<th>NA64-2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>data-taking efficiency (d-t time/beam time)</td>
<td>0.80</td>
<td>0.87</td>
</tr>
<tr>
<td>DAQ lifetime, $5 \times 10^6e^-$/spill</td>
<td>0.83</td>
<td>0.87</td>
</tr>
<tr>
<td>Overall lifetime</td>
<td>0.75</td>
<td>0.82</td>
</tr>
</tbody>
</table>

from the results of measurements at different distances $L$ and beam energies. Finally note, that the performed analysis for the sensitivity of the proposed experiment may be strengthened by more accurate and detailed simulations of the H4 beam line and concrete experimental setup.

We also plan to install and test several straw tube chambers (STC) with the straw diameter of 6 mm (2 STCs) and 2 mm (2 STCs). These STCs have been designed with the aim to distinguish and reconstruct two close tracks from the visible $X$ decay mode, such as $A' \rightarrow e^+e^-$. Compared with the setup of 2016, the following main modifications will be used in 2017.

6 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 2017 run. These items are listed and briefly discussed below in this report.

6.1 Detector upgrades for the 2017 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 2017 run. The upgrades proposed are designed to improve the reliability of the detector and to improve the trigger/DAQ livetime. The NA64 performance from the 2016 run and our goals for the 2017 are summarized in Table 7. The improvement in data-taking efficiency will come mainly from the replacement of DAQ components, partly described in section 2.12. Several modifications to the trigger and front-end readout are required to achieve the livetime improvement; these modifications are described in Section 4.5. 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 .5 weeks to a 5 week run.

To increase the overall signal efficiency and improve background rejection the following upgrade of the setup will be installed:

(i) additional number of the MM, GEM, ST stations
(ii) two fast beam hodoscopes in the upstream part of the setup

(iii) transversely segmented PbSc SRD detector with improved readout

(iv) zero-angle veto to suppress bremsstrahlung photons

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

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

(vii) Further developments of the DAQ and the analysis program are in progress to ensure a substantial data collection of \( n_{\text{eot}} \simeq 10^{11} \) events in 2017.

(viii) At present, the manpower does appear to be adequate to complete the task in a timely manner. We are convinced that our plans to complete conclusive analysis by August are realistic. And first results on either observation of the signal or exclusion area derivation will be available.

To test the intensity of the \( e^- \) beam up to \( \gtrsim 7 \cdot 10^6 \text{ e}^-/\text{spill} \). In October'16 the detector was tested up to \( 5 \cdot 10^6 \text{ e}^-/\text{spill} \) or \( \approx 10^{10} \text{ e}^-/\text{collected during one day for the ”normal” SPS operation with } \sim 2 \text{ supercycles per minute. Good performance of the setup was demonstrated. With intensity } \sim 7 \cdot 10^6 \text{ e}^-/\text{spill} \text{ accumulation } \approx 10^{11} \text{ e}^- \text{ during one week - 10 days of running is feasible.}

6.2 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 \( m_{A'} \lesssim 1 \text{ GeV} \) the number of accumulated electrons on target is required to be around \( n_{\text{eot}} \gtrsim 10^{12} \) or more, and a very low background rate. Assuming the beam rate to be around \( 5 \cdot 10^6 \text{ e}^-/\text{spill} \) 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 the scratch and its debugging takes already about 3 days. Alignment, detector calibration and tuning takes additional 3-4 days more. In 2017 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 the 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.

7 Competition

The theoretical status of the $^8\text{Be}$ anomaly has been discussed by J. Feng in his talk at the recent CERN-EPFL-Korea Theory Institute “New Physics at the Intensity Frontier”. It will be also extensively discussed at a forthcoming workshop focusing on potential new small-scale projects in the U.S. Dark Matter search program, which will be held at the University of Maryland, College Park March 23-25, 2017. According to agenda a few talks devoted to the possible searches for $\text{Be}$ excess events are foreseen.

In Fig. 1, one can see that experiments such as MESA, Dark Light, VEPP-3 potentially could probe the $X$ parameter space. Among them probably the Dark Light experiment at JLab is the most serious competitor. The current status of the DarkLight experiment at JLab is not precisely known, but they had a run in 2016. They are sensitive to short lived dark photons in the mass range $10 \text{ to } 100 \text{ MeV/c}^2$. The Dark Light techniques is based on precisely measured electron proton scattering using the 100 MeV electron beam of intensity 5 mA at the JLab energy recovering linac incident on a windowless gas target of molecular hydrogen. The experiment is intended to run at least a couple of years.

Another experiment aiming at the study of the $X \rightarrow e^+e^-$ decay modes by exploiting the new Mainz Energy Recovering Superconducting Accelerator (MESA, see Fig. 1) in Mainz. The plan is to reach a sensitivity down to the level of $\epsilon \simeq 10^{-3}$ in the mass range $m_X \lesssim 20 \text{ MeV}$ in about two years. This is a competitor to NA64 although their plan is to be commissioned in 2020. Here, however, one should take into account the LS2 period 2019-2020 at LHC during which the NA64 also will not run.

8 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 five weeks of running in 2017 is to address three areas of great interest in dark sector physics:
1. to continue the search for the $A' \rightarrow \text{invisible}$ decay and to reach sensitivity level allowing to probe significant fraction of the theoretically interesting parameter space ($10^{-6} \lesssim \epsilon \lesssim 10^{-3}; m_{A'} \lesssim 1 \text{ GeV}$);

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

3. continue our studies of $Z_{\mu} \rightarrow \text{invisible}$ 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 2017 data sample should have better properties than the 2016 data. As the offline analysis proceeds, we also continue to learn how to take better data in 2017. Experience gained in the 2017 run 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 2017-18 to accumulate as much as possible EOT for the physics goals described above. Thus assembling the NA64 detector at H4 line in 2018 prior the SPS run would be very helpful.

We also propose to continue our program of muon and hadron physics which has already produced a number of interesting results.

9 Publications

Since the last NA64 SPSC report in 2015 and approval of the experiment in March 2016, the collaboration has completed the publication on the simulation of the $A' \rightarrow \text{invisible}$ signal in the NA64 detector, of the physics analyses of the search for the $A' \rightarrow \text{invisible}$ decay based on the July 2016 data sample, and prepared two reference publication on the NA62 subdetector:
More analyses are in preparation for review within the NA64 Collaborations and timely publication.

(i) NA64 collaboration: "Improved limits on invisible decays of sub-GeV dark photons at the CERN SPS", based on October 2017 data.

(ii) NA64 collaboration: "Search for invisible decays of sub-GeV dark scalars at the CERN SPS", based on October 2017 data.

(iii) NA64 collaboration: Tracking in high intensity beam with Multiplexed XY Resistive Micromegas detectors, based on July and October 2016 data.

The NA64 Collaboration contributed to several topical Workshops with NA64 Detector contributions and recently published or preliminary physics results from data analyses. During the period from March 2016 to June 2017, the NA64 speakers presented 6 talks. More contributions including the International Conferences, are also planned in 2017.

10 Acknowledgments

The success of NA64 is in large part due to the tremendous effort expended by many physicists, graduate students, engineers, and technicians. Some of these people will not be involved directly in the 2017 run, but their contributions to NA64 will be felt in 2017 and beyond.

Particularly noteworthy have been the contributions of the following people: V. Tikhonov, S. Zvyaginzev, O. Suvorova (IHEP),

References


[34] http://cern.ch/sba