NA64—Search for Dark Sector Particles

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1 Introduction

One of the main triumphs in the field of science and knowledge was a theory, developed in stages, through the works of various scientists along the latter half of the 20th century that explains nearly everything that rule our daily lives—from the fundamental structure of matter and energy to reactions that power the sun, from understanding the first moments of our universe's existence to the building blocks of our being. Physicist Robert Oerter called it "The Theory of Almost Everything" in his book named the same [1], but it is more commonly called the "Standard Model of Elementary Particles". The Standard Model consists of the fundamental particles called the fermions that include the quarks and leptons. It also includes the gauge bosons which are the force carriers as well as the Higgs boson that is responsible for the origin of mass [2]. Even though the Standard Model has been successful in explaining almost everything, it falls short in being a complete theory of fundamental forces and fails to explain some phenomena. The Dark Matter, for example is not part of the Standard Model and points to physics "Beyond the Standard Model". One of the hypothesis for Dark Matter points to an existence of a dark sector with its own particles and forces similar to the Standard Model as shown in Fig. 1. This sector exists in parallel with our "normal" sector and will not interact with it via known forces except via gravity. However, there can be some additional interactions via some portals (Review available in [3]). Analogous to electromagnetism of our world, for which the massless gauge boson, the photon, transmits force between charged particles, there could be a dark electromagnetism with a possibly massive gauge boson, called the dark photon that transmits the forces between dark particles. Our photon can interact with a dark photon within a certain mass range and coupling strength resulting in a new additional interaction between our and the dark sector. In

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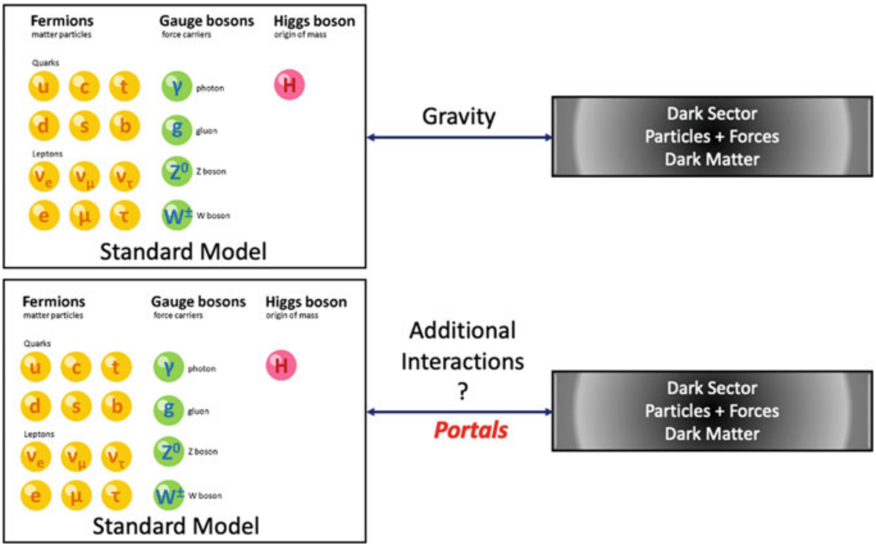


Fig. 1 Standard model of elementary particles and the dark sector including dark matter interacting via gravity as well as some additional interactions via portals

the most interesting class of models the A' is light with sub-GeV masses and have a $\gamma - A'$ coupling strength, $\epsilon << 1$ and in the range which can be experimentally tested.

An additional motivation for new dark particle searches comes from the observed discrepancy between the predicted and the experimental values of the anomalous magnetic moment, $(g-2)_\mu$ of the muon [4]. All elementary particles are like a spinning top and thus has an intrinsic angular momentum called the spin. When a charged particle spins, including the muons, it will generate their own magnetic field. The strength of this magnetic field is referred to as the magnetic moment or the g-factor. Any deviation from the theoretical prediction of this g will point to new physics. Almost two decades ago the Brookhaven National Laboratory presented their first results where a 3.6σ deviation was observed in the $(g-2)_\mu$ [5]. In 2021 the results were confirmed by Fermilab with a 4.2σ discrepancy [6]. Calculations have shown that this could be possible if a sub-GeV dark boson, Z_μ, which interacts presumably only with muons (and tau leptons) with a coupling strength, $\epsilon \sim 10^{-3}$, exists (as the A' explanation for the $(g-2)_\mu$ anomaly has since been excluded). Similar to the dark photon, the Z_μ could also induce additional interaction between the ordinary and dark sectors not predicted by the Standard Model. That model is very attractive as it could explain both the $(g-2)_\mu$ anomaly and the Dark Matter puzzle (see Sect. 4)

The most effective search for the A' is through its decays. Depending on the mass of the A' it can decay either visibly to Standard Model leptons, $1 = e, \mu$ or hadrons when the $M_{A'} > 2M_l$ where $M_{A'}$ is the mass of the dark photon and M_l is the mass of the leptons. The A' could also decay invisibly to dark states with masses $<M_{A'}/2$. When NA64 started its run the $(g-2)_\mu$ explanation for A' decaying visibly only had been excluded by previous beam dump, fixed target, collider and rare meson decay experiments [7]. NA64 therefore started with focussing on the $A' \to invisible$ decay search.

2 NA64 Experiment

NA64 is an experiment at the CERN SPS approved in March 2016 with the goal to search for $A' \to$ invisible decay with an electron beam [8]. A dark photon can be produced in any reaction that can produce a normal photon. When an electron beam hits a target material it produces bremsstrahlung photons. The dark photons can then be produced via its mixing with the normal photon. NA64 aims to exploit this interaction to search for the dark photons.

2.1 Principle of the Experiment

NA64 is a fixed target experiment that combines the beam dump technique with missing energy measurement searching for invisible decays of massive A' produced in the reaction:

$$e^- Z \to e^- Z A' \tag{1}$$

It employs the 100 GeV electron beam from the CERN SPS H4 beamline. The beam is dumped on the active target, the ECAL, as shown in Fig. 2. The beam with energy $E_0 = 100$ GeV interacts in the target and deposits an energy, E_{Ecal}, in the ECAL. The A' if produced carries the remaining energy $E_0 - E_{Ecal}$. After escaping the target the A' then decays into dark matter particles. As the dark matter particles will not interact with the downstream detectors and energy should be conserved the undetected energy of $E_0 - E_{Ecal}$ above a certain threshold gives the signal of the dark photon. In the situation when A' is not produced the remaining energy is carried by Standard Model particles which are detected in the downstream part of the NA64 setup as E_{Hcal}. The threshold for the missing energy set by NA64 is 50% of the incident energy so a missing energy >50 GeV indicates a positive signal for the A' search. The complete setup of NA64 is shown in Fig. 3. As NA64 is looking for missing energy there are three main sources of errors that should be minimised.

1. The incoming energy of the beam itself is <50 GeV → If the incoming energy of the beam is <50 GeV and the beam deposits all its energy in the ECAL, E_{Hcal} will be zero and will mimic a missing energy signal.

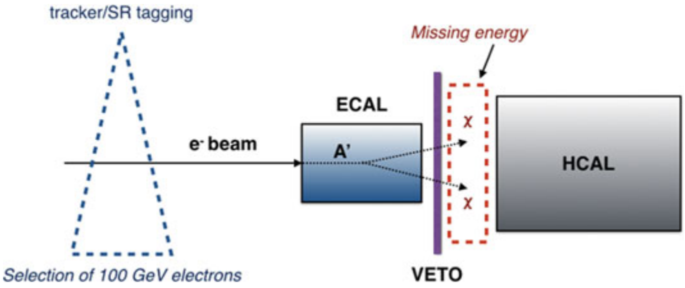


Fig. 2 Schematic for the NA64 invisible decay search

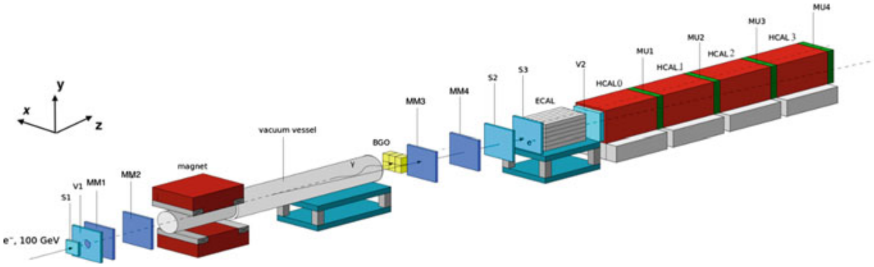


Fig. 3 Full setup of NA64 for the invisible search

2. The incoming beam is not an electron → If the incoming beam has any contamination of hadrons which are not identified this can also create background for the search.
3. There is an energy leak from the downstream part → If the NA64 setup does not detect part of the energy downstream it can mimic a missing energy signal.

The methods used to suppress the backgrounds are discussed in the following subsections.

2.1.1 Suppression of Low Energy Beam Electrons

In order to prevent misidentification of energy of the incoming beam NA64 comprises of a tracking section in its upstream part that includes the MM1-4, which are the tracking stations giving the hit positions of the beam on these planes, and the magnet as shown in Fig. 3. Any charged particle in a magnetic field moves in a circular motion with the radius depending on its momentum for a given magnetic field as:

$$p = qBr \tag{2}$$

where p is the momentum of the beam, q is the charge, B is the magnetic field and r is the radius of curvature. Therefore for a known B and the calculated r from the hit

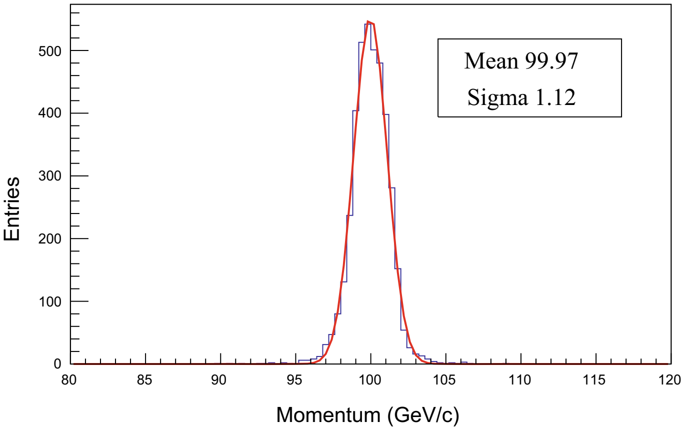


Fig. 4 Momentum resolution for the reconstructed momentum in NA64

positions of the particle in the tracking stations one can measure the momentum of the incoming beam. NA64 uses a 7 T.m dipole magnet for the momentum reconstruction and tracking detectors with a spatial resolution ∼100 µm [9]. The resolution of the reconstructed momentum is ∼1% for a 100 GeV beam as shown in Fig. 4.

2.1.2 Suppression of Hadron Contamination

A charged particle in a magnetic field moves in a circular motion emitting photons along its trajectory called the synchrotron radiation. The total power, S, emitted per unit length by a relativistic charged particle of energy E with mass M and with bending radius r in a magnetic field B perpendicular to its velocity is given by:

$$S = \frac{q^2 c}{6\pi} \frac{1}{(Mc^2)^4} \frac{E^4}{R^2} \tag{3}$$

where q is the charge of the particle and c is the speed of light. The synchrotron photons are emitted tangentially to the particle trajectory. As seen from the Eq. 3 the total emitted power scales inversely with the fourth power of the charged particle mass. Therefore, the synchrotron radiation emitted by heavy charged particles is orders of magnitude less than the light ones and can be used to suppress them. Heavy charged particles like $\mu^{+/-}$ and $\pi^{+/-}$ which has about 200 e^- mass, radiate $\sim 10^9$ times less than an electron. However this is true for ideal vacuum, which is unlike real experimental setup where interaction of hadrons in vacuum windows, residual gas, instrumentations etc., limit the suppression factor due to emission of secondary particles with enough kinetic energy (several MeVs) that mimics the synchrotron radiation of an electron. This was checked during the beam time and validated with

Monte Carlo simulation. The suppression factor thus achieved in NA64 $< 10^{-3}$ for the hadrons with a beam contamination of $\pi/e < 10^{-2}$ [10].

2.1.3 A Fully Hermetic Detector

The $A' \to$ invisible search requires not only a precise knowledge of the incoming beam but also an accurate measurement of the missing energy from the incoming beam's interaction. The electromagnetic calorimeter is crucial to determine precisely the deposited energy by the incoming electron in the active target and hence calculate the missing energy downstream. An electromagnetic calorimeter, the ECAL, with $\sim$40 radiation lengths (X_0) is used in NA64. A radiation length is the characteristic distance traversed by an electron before it loses its energy by a factor of $\frac{1}{e}$ via electromagnetic interaction. Therefore the 40 radiation lengths ensure that all the energy from electromagnetic interaction will be deposited within the ECAL for a precise measurement of the energy. As discussed the knowledge of E_{Ecal} is extremely important to estimate the missing energy.

The longitudinal hermeticity of the experimental setup is enhanced by using hadronic calorimeters, the HCAL modules, to detect charged and neutral hadrons and subsequently provide a measurement of the missing energy, not detected in the ECAL, after proper tagging of the incoming particle with the trackers and synchrotron radiation detectors. The HCAL consists of four modules, each comprising of 7 interaction lengths. An interaction length is the mean distance that a hadronic particle covers before undergoing an inelastic nuclear interaction. Therefore a total of 28 interaction lengths with the four HCAL modules ensure that any hadron that escapes the ECAL will interact in them and be absorbed which will give a precise measurement of the energy, E_{Hcal}.

Under Standard Model interactions:

$$E_{Ecal} + E_{Hcal} = E_0 \tag{4}$$

where E_0 is the energy of the incoming particle and for the dark photon signal:

$$E_{Ecal} + E_{Hcal} < 0.5E_0 \tag{5}$$

Since the signal is characterized by "No Interaction" in the HCAL the zero energy threshold had to be checked for the detectors as well. In order to estimate the zero energy event threshold Monte Carlo simulations were performed and compared with data for a 100 GeV electron beam. The threshold for the HCAL for a zero energy event was then set at 1 GeV i.e., if $E_{Hcal} < 1$ GeV it is taken as a zero energy event.

With these selection criteria the data collected by NA64 have been analysed and the current results from the invisible decay search are detailed in the following Section.

3 Current Results of the NA64 A’ → Invisible Search Experiment

Since 2016 NA64 has collected ∼3×10^{11} electrons on target until 2018. The analysis of the 2016 data has been completed and that for the 2017–2018 data is currently being finalised. The missing energy signal has been searched with the selection

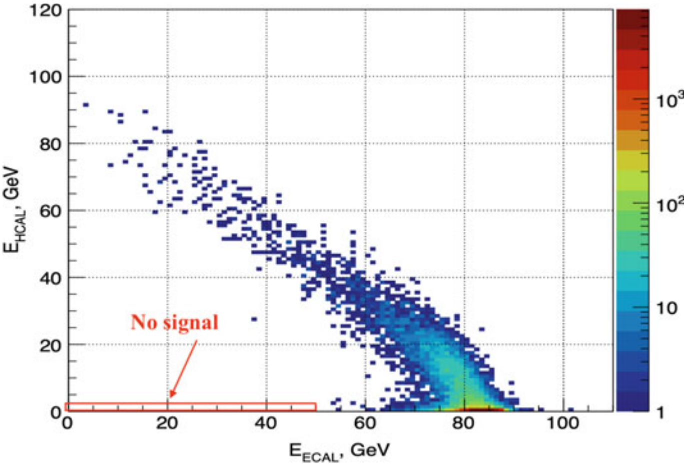


Fig. 5 The energy in the HCAL as a function of the energy in the ECAL as detected in NA64. The red box corresponds to the signal region for A’ which shows no event

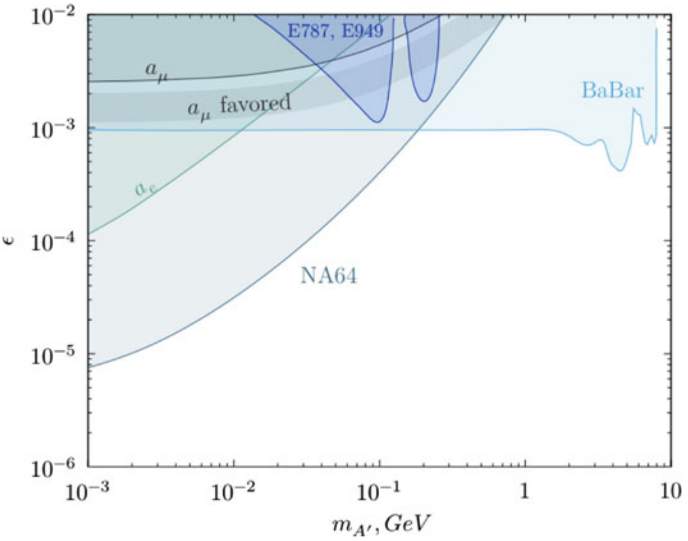


Fig. 6 The coupling strength, ϵ, and mass, $M_{A'}$, parameter space of the A' including the region excluded by NA64 with full statistics collected between 2016 and 2018

criteria described above. Figure 5 shows the 2-dimensional plot of the energy in the HCAL as a function of that in the ECAL. The red box corresponds to the signal region where the $E_{Ecal} < 0.5E_0$ and E_{Hcal} corresponds to no signal i.e., ≤1 GeV. As no event has been detected in the missing energy measurement NA64 was able to exclude a considerable region of the coupling strength—mass parameter space of the A' as shown in Fig. 6 [11]. This also includes the A' explanation of $(g-2)_\mu$ which thus could be excluded for the invisible decay channel. With more statistics NA64 would be able to put very competitive limits on the parameter space for the sub-GeV dark matter or potentially discover the dark photon.

4 Additional Searches for Dark Particles

Although NA64 was primarily designed for the $A' \rightarrow$ invisible search it can also be used for other complementary searches. As discussed above A' could also decay visibly into Standard Model leptons depending on its mass. NA64 could also search for these visible decays with a small modification to its setup as shown in Fig. 7. In this case a 100 GeV electron beam is incident in a similar way on an active target, WCAL. If the A' is produced it will escape the WCAL and will be undetected in the downstream detector the V2. Then it will decay into the e^+e^- pair which can be detected with the trackers downstream. Therefore, the visible search can be equated to a "light shining through a wall" signature. During the 2017 and 2018 runs NA64 has collected upto 8×10^{10} electrons on target in this mode. The data has been analysed and no event has been detected in the signal region. NA64 was thus able to exclude part of the parameter space for the visibly decaying dark photon as well as shown in Fig. 8 [12].

In addition NA64 also plans to search for the dark sector through particles that predominantly couple to muons and taus, the heavier counterparts of the electrons with its experiment called the NA64μ [13]. As mentioned the A' explanation for the $(g-2)_\mu$ anomaly has already been excluded, however dark sector models suggest that there can be new massive gauge boson, Z_μ which couples predominantly to μ and τ and can explain this discrepancy [14]. This is an additional motivation for such searches along-with dark matter. Such particles can be searched for in a μ

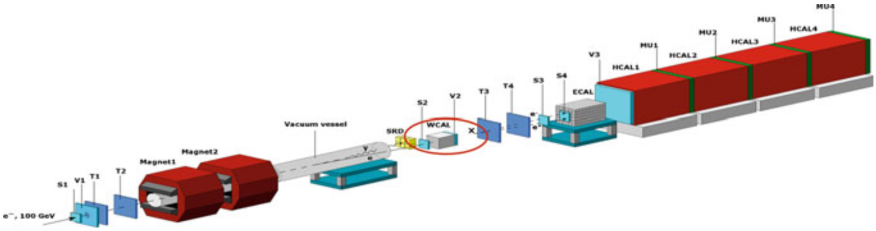
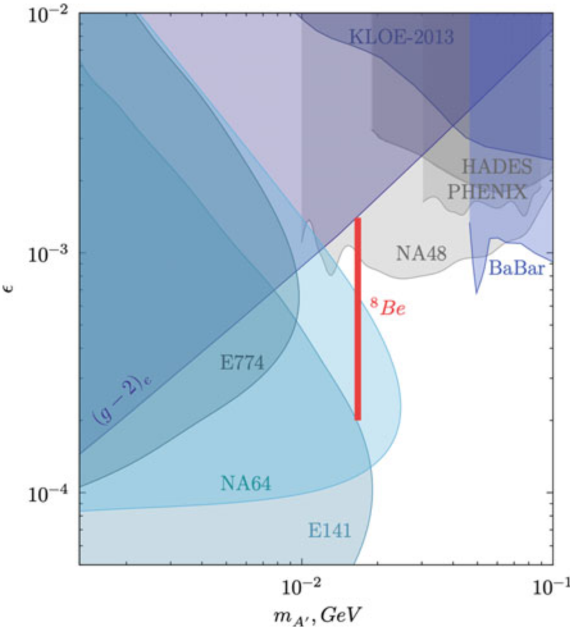


Fig. 7 Full setup of NA64 for the $A' \rightarrow$ visible search

Fig. 8 The parameter space excluded by NA64 for the $A' \to$ visible channel using the 2017 data (blue shadowed region) and the 2017+2018 data (dashed line, preliminary)



interaction for example. NA64 therefore plans to extend its electron beam search with muon beams using the M2 beamline at the CERN SPS.

The M2 beamline at the CERN SPS delivers high intensity high energy muon beams [15]. NA64 plans to exploit this beamline to search for $Z_\mu \to$ invisible decays. The search mechanism is slightly different compared with the electron beam as muons are much heavier than electrons and therefore does not get stopped in the ECAL. For this search a 160 GeV muon beam is momentum selected with the NA64 spectrometer similar to the electron beam described above. The muon beam is then incident on the ECAL where the beam interacts to potentially produce the Z_μ via interaction of the muon on the target. In case of the Z_μ production it carries majority of the energy $>0.5E_0$ where E_0 is the incident muon beam energy, and subsequently decays into dark matter particles which remains undetected in the downstream part of the setup similar to the $A' \to$ invisible case. However, unlike the electrons the muons will not deposit its energy but will carry the remaining $<0.5E_0$ and escape the ECAL. Therefore there are downstream trackers with spectrometer magnets similar to the one for the incoming momentum reconstruction to reconstruct the momentum of the outgoing muon. This search is therefore not a missing energy search but a missing momentum search. The schematic of the setup is shown in Fig. 9. The signal includes that the reconstructed momentum of the outgoing muon <80 GeV/c and there is no energy in the ECAL and HCAL while the reconstructed momentum of the incoming muon is ~160 GeV/c. In 2021 November NA64 had its first pilot run for the muon beam in the M2 beamline and accumulated $\sim 5 \times 10^9$ μ on target. The first aimed

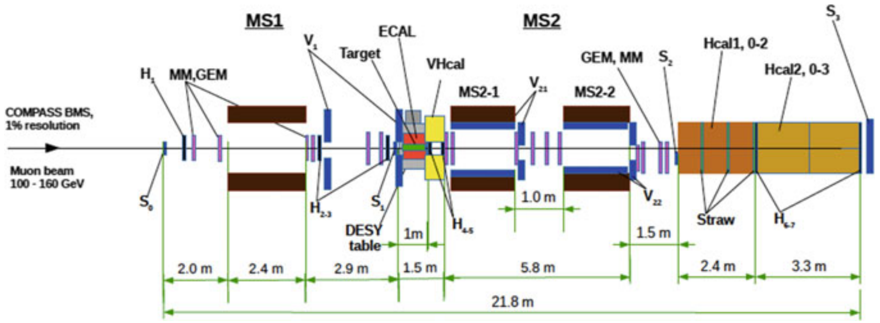


Fig. 9 Full setup of NA64 for the $Z_\mu \to$ invisible search

milestone for NA64μ is to collect 10^{10} μ on target to be able to cover the $(g-2)_\mu$ favoured parameter space. In 2022 2–3 weeks of beam time have been requested to potentially reach this goal.

5 Summary

Dark Sector physics can be effectively probed with the NA64 experiment and its search techniques in the medium-term future. NA64 uses two complementary approaches including beam-dump and missing energy/momentum and can either discover or rule-out nearly all predictive models of sub-GeV thermal Dark Matter. By the Long Shutdown 3 in 2025 NA64 aims to collect $\sim 5 \times 10^{12}$ electrons on target and with the improved statistics NA64 can probe most of the existing thermal Dark Matter models [16]. With the restart of the CERN accelerator complex in 2021 and the planned runs the new results are expected to be extremely promising and exciting.

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