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Search for exotic particles at NA62

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NA62 is successfully running in the North Area of the CERN SPS with the main goal of measuring the $BR(K^+ \to \pi^+ \nu\overline{\nu})$ with 10% accuracy. Owing to the high beam energy and high beam intensity, the long decay volume and the hermetic detector coverage, NA62 also has the opportunity to directly search for a plethora of hidden-sector particles, both in visible or invisible final states.

A large variety of searches for hidden sector particles can be performed using kaon decays and broad and rich physics programme is being proposed for the 2021-2023 data taking, including $\sim 10^{18}$ protons-on-target (pot) collected when the experiment is operated in dump mode. We will detail the status of the first analysis based on the 2×10^{15} pot already collected in dump mode.

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1. Introduction

The Standard Model of particle physics (SM) provides currently a complete and self-consistent description of known elementary particles which interacts via strong, weak and electromagnetic forces. The SM along with general relativity is also very successful in describing the evolution of the Universe as a whole.

However, the Standard Model currently fails to explain a number of observed phenomena in particle physics, astrophysics and cosmology, as neutrino masses and oscillations, dark matter, and baryon asymmetry of the universe.

So far the experimental efforts have been concentrated towards the discovery of new particles and interactions with masses at (or above) the EW scale and with sizeable couplings to SM particles. Another viable possibility, largely unexplored so far, is that these particles responsible of the still unexplained phenomena beyond the SM are below the EW scale and have not been detected because they interact very feebly with SM particles.

Having lost the EW scale as the reference scale for new phenomena to appear, an increasingly accepted approach in the particle physics community is to extend the SM with the simplest UV-completed and gauge-invariant set of fields and interactions which are sufficient to account for the experimental evidence of still unexplained phenomena.

The minimal set of particles needed to explain the BSM phenomena are three right-handed singlet neutrinos which generate Majoranas masses and oscillations for the three SM neutrinos through the see-saw mechanism [1, 2, 3, 4] and are responsible of the baryogenesis through leptogenesis [5, 6], and some Dark Matter (DM) candidate which, if in the sub-GeV mass range, requires light mediators to deplete the overabundance in the early Universe [7, 8, 9, 10, 11, 12].

In the Neutrino Minimal Standard Model (νMSM) [13, 14, 15, 16, 17, 18] three right-handed neutrinos (Heavy Neutral Leptons, HNL) which account for the neutrino masses, the DM and the baryon asymmetry of the Universe are added to the SM. While in most see-saw models the HNLs live much above the EW scale [19, 20, 21], in the νMSM they are lighter. The lightest state (N_1) is in the o(10) keV range, and act as DM candidate, while the two heavier ones ($N_{2,3}$) can have a mass in the range 1-100 GeV. However, if $N_{2,3}$ have masses in the GeV range a very large lepton asymmetry may be produced in the early Universe at temperatures below 100 GeV and this large asymmetry can boost the production of a keV sterile neutrino DM later in the history of the Universe. The survival of the lepton asymmetry opens the possibility to tie the properties of the HNLs responsible for baryogenesis and for Dark Matter and use astrophysical constraints to limit HNL masses to below a few GeV.

If the HNLs have a mass much higher than the EW scale [5, 6], still they can explain the origin of neutrino masses and oscillations and baryogenesis through leptogenesis but do not account for DM, for which a separate mechanism has to be introduced. The idea that dark matter is a thermal relic from the hot early Universe motivates non gravitational interactions between dark and ordinary matter. The canonical example involves a heavy particle with masses of $10^2 - 10^3$ GeV interacting through the weak force (WIMPs). No WIMP has been detected so far. A thermal origin is equally compelling even if DM is not a WIMP: DM with any mass from tens of keV to tens of TeV can achieve the correct relic abundance by annihilating directly into SM matter. However thermal DM in the MeV-GeV range with SM interactions is overproduced in the early Universe so viable scenarios require additional SM neutral mediators to deplete the overabundance [7, 8, 9, 10, 11, 12]. These hidden sector mediators are light, long-lived, feebly-interacting particles and mix with SM fields that do not carry electromagnetic charge, like the Higgs and the Z bosons, the photon and the neutrinos.

For example, the explanation of the positron excess (as measured by PAMELA [22, 23, 24], FERMI [25], AMS-2 [26]) in cosmic ray spectra in terms of DM annihilation requires the interaction of the dark and SM sectors via a light mediator. The GeV and sub-GeV range for mediators is favoured for two independent reasons. First, the extra attraction between DM particles created by the exchange of light mediators helps to tie the cross-section needed to explain the cosmic-ray positron excess to a well-determined DM annihilation cross section in the early Universe. Secondly, the mediator mass should be below twice the proton mass ($\sim$2 GeV) to avoid producing too many antiprotons in cosmic rays. Light thermal DM scenarios can be classified by the spins and masses of the DM and mediator, and by the mediators interactions with both DM and SM matter. SM symmetries substantially restrict the latter interactions: vector mediators can mix with the photon or weakly gauge a SM global symmetry, while scalars can mix with the Higgs (or have axion-like couplings in extensions of the SM).

A vibrant and lively search for light DM and the corresponding mediators in the MeV- GeV range is currently ongoing at CERN (NA48/2 [27, 28], LHCb [29, 30], NA64 [31]); at Jefferson Lab (APEX [32, 33]), HPS [34], BDX [35], DarkLight [36]), at Fermilab (MiniBoone [37], SeaQuest [38]); in Japan at KEK-II (Belle2,[39]); in Germany at Mainz (Mesa [40, 41]); in Russia at Budker Institute [42] and in Italy at Laboratori Nazionali di Frascati (KLOE [43, 44, 45, 46, 47, 48], PADME [49]).

The search for long-lived particles in the MeV-GeV range is one of the main topics of the Physics Beyond Colliders activity at CERN [50] whose mandate is to exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments. Several proposals (FASER [51], CODEX-b [52], MATHUSLA [53], MilliQan [54], RedTop [55], LDMX [56] SHiP [57], are currently being considered within this Study Group, mostly served by existing or proposed lines of high energy protons, electrons, and muons extracted from the CERN SPS. The NA62 [58] experiment aims at using a primary beam of 400 GeV protons dumped on a high-Z material to search for hidden sector particles decaying into visible final states.

2. The NA62 experiment

The NA62 experiment aims at measuring the BR($K^+ \to \pi^+ \nu\bar{\nu}$) with an accuracy of 10%. It is currently taking data in the experimental hall ECN3 served by the K12 beam line in the CERN North area. The layout of the experiment is shown in Figure 1.

In the NA62 beam line, the primary protons are transported over a distance of $\sim$900 m towards a 400-mm long, 2-mm diameter cylindrical Beryllium (Be) target used to produce a secondary positively charged 750 MHz hadron mixed beam of 75 GeV/c momentum. The secondary beam

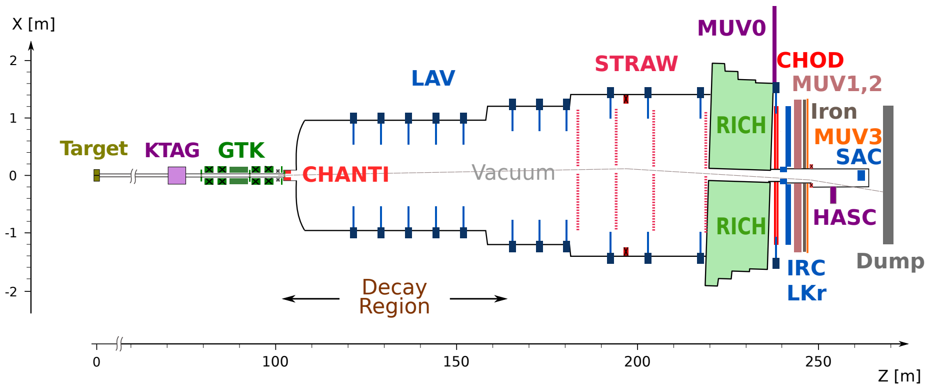

Figure 1: Layout of the NA62 experiment.

reaches the 65-m long, 2-m diameter, in-vacuum decay volume of the NA62 experiment 100-m downstream the Be-target.

About 100 m downstream of the target the secondary beam reaches the 120m long evacuated decay volume which has a diameter of 2 m. About 6% of the hadron beam are kaons, which are identified and timestamped by a N_2 filled Cherenkov counter located along the beam line. Three silicon pixel stations measure momentum and time of all the particles in the beam at a rate of 750 MHz. A guard ring detector tags hadronic interactions in the last pixel station at the entrance of the decay volume. Large angle electromagnetic calorimeters made of lead glass blocks surrounding the decay vessel are used to veto particles up to 50 mrad. A magnetic spectrometer made of straw tubes in vacuum measures the momentum of the charged particles. A Ring-Imaging Cherenkov (RICH) counter filled with Neon separates π, μ and e for momenta up to 40 GeV. The time of flight for charged particles is measured both by the RICH and by the scintillator hodoscopes placed downstream of the RICH. An electromagnetic calorimeter covers the forward region and complements the RICH for the particle identification. The hadronic calorimeter provides further separation between π and μ based on hadronic energy and a fast scintillator array identifies muons with sub-nanosecond time resolution.

At the nominal beam intensity of 3×10^{12} protons per pulse, with pulses of 4.8 s, the NA62 experiment can collect up to 3×10^{18} protons on target (pot) per year.

The experiment can be operated in two different modes, the *kaon mode* and the *beam dump mode*. In the *kaon mode* the SPS 400 GeV proton beam hits a fixed target and produces a secondary positively charged hadron beam with a momentum of 75 GeV, which comprises to ~ 6 % of charged kaons. Charged kaons are then used to search for the rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ which is the primary purpose of the experiment.

In the *dump mode* the target is removed and the beam is directly sent into a dump, producing large numbers of mesons and leptons of all sorts. When the experiment is operated in the dump mode, the target is pulled up and the primary proton beam is send directly onto the $Cu-Fe$ based collimators that act as a hadron stopper (or dump) located 20 m downstream of the target. In this configuration, about 2×10^{15} D-mesons and $\sim 10^{11}$ $b-$hadrons are produced from the 10^{18} pot, which correspond to about 80-100 days of data taking at the nominal NA62 beam intensity.

Results obtained with the 2016 dataset [59] show that an accuracy of about 20% can be reached with the data collected in the current (2016-2018) run, and two extra more years of data taking after the long shutdown 2 (2019-2020) are necessary to reach the final goal. Hence a broad and compelling physics programme is being envisaged for the 2021-2023 run, with a large majority of the time dedicated to kaon physics and about one integrated year of beam time in 2023 dedicated to hidden sector physics in dump-mode.

3. NA62 sensitivity to hidden sector particles when operated in dump-mode

Hidden sector particles can be originated by the decay of beauty and charm hadrons, and by photons produced in the interactions of protons with the dump. Their couplings to SM particles are very suppressed leading to expected production rates of 10^{-10} or less. The smallness of the couplings implies that the hidden sector mediators are also very long- lived (up to $\tau \sim 0.1$ sec) compared to the bulk of the SM particles. Therefore the decays to SM particles can be optimally detected only using an experiment with decay volume tens of meters long followed by a spectrometer with particle identification capabilities. The NA62 detector, perfectly fits these requirements.

The expected sensitivity of NA62 with a dataset of 10^{18} pot for Heavy Neutral Leptons (HNLs) in the plane defined by the interaction strength versus the mass is shown in Figure 2 for the three scenarios with single flavor dominance. Shaded areas are excluded regions by past experiments [60] and dotted lines are expected sensitivities of future experiments [61, 51, 53, 52, 57]. The allowed parameters range is defined by the seesaw mechanism and Big Bang Nucleo-synthesis (BBN) lines [62, 63], and the (model-dependent) Baryon Asymmetry of the Universe (BAU) line [64]. The sensitivity curves assume to detect all 2-track final states with zero background and include the geometrical acceptance and the trigger efficiency. The selection efficiency is assumed to be 100%, however the inclusion of the selection efficiencies is expected to worsen the limits by 20% at most.

The range of couplings that is testable by the NA62 experiment is perfectly compatible with recent fits on present neutrino oscillation data [65].

The sensitivities achievable with 10^{18} pot for a vector mediator (Dark Photon) decaying to dimuon final states, for a scalar mediator (Dark Scalar) decaying to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ and K^+K^- final states, and for an Axion Like Particle (ALP) decaying to 2-photon final states [66] are shown in Figures 3 left, center and right, respectively. In all plots the shaded areas are excluded regions by past experiments and dotted lines are expected sensitivities of future experiments. The effect of the geometrical acceptance and the trigger efficiency is included and zero-background is assumed.

4. Analysis of the data collected in dump-mode

The sensitivity to hidden sector particles can be greatly spoiled by the presence of background. In fact, the proton interactions with the dump, along with hypothetical hidden sector particles, give rise to a copious direct production of short-lived resonances, and pions and kaons. While the collimators length ($\sim$22 interaction lengths) is sufficient to absorb the hadrons and the electromagnetic radiation produced in the proton interactions, the decays of pions, kaons and short-lived resonances

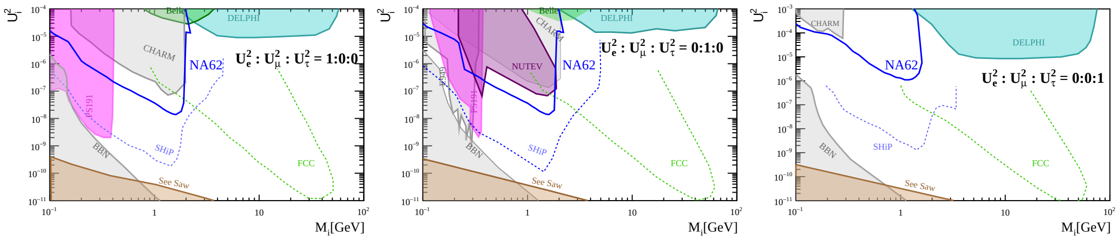

Figure 2: Projections of the NA62 sensitivity (90% CL exclusion limit) for 10^{18} pot in the coupling versus mass plane for HNLs originated by the dump (blue solid lines) under the hypothesis of single-flavor dominance, hence: $U_e^2 : U_\mu^2 : U_\tau^2 = 1:0:0$ (left), $0:1:0$ (center) and $0:0:1$ (right). The sensitivity below the kaon mass comes mostly from kaon experiments, as, for example, in Ref. [67].

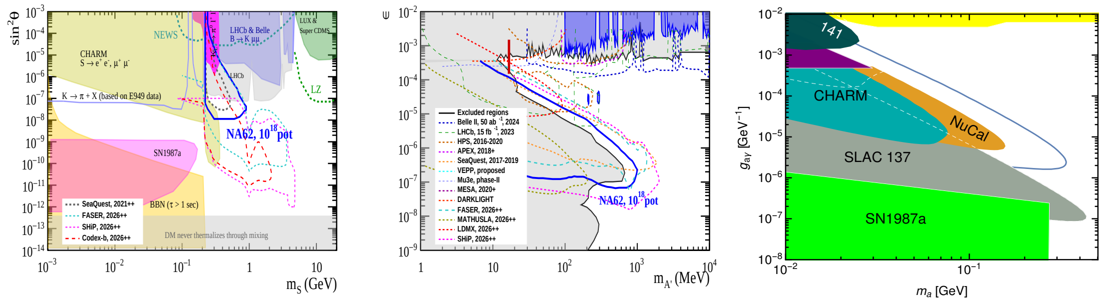

Figure 3: Projections of the NA62 sensitivity (90% CL exclusion limit) for 10^{18} pot in the coupling versus mass plane for Dark Scalar (left, blue solid line), Dark Photon (center, blue solid line), and ALPS with photon-coupling (right, blue solid line) originated by the dump.

result in a large flux of muons and neutrinos. Muons and neutrinos from the dump cause two major sources of background for hidden sector searches.

A 10-hours long run in dump mode has been performed by NA62 in November 2016 in preparation for long run in dump mode in 2023, and 2×10^{15} pot have been collected. This sample has been used for preliminary measurements of rates and topologies of the main background components. No background simulation can compete with this dataset: in fact, not more than 10^{11} pot ($\sim$ 3% of a single NA62 spill) can be simulated with GEANT, running on a large CPU-farm for several weeks. Only specific MC samples can be produced once the main backgrounds are identified. To date about $\times 10$ more data in dump mode have been collected and the analysis is in progress.

About 50 kHz of tracks have been measured in the NA62 acceptance, fully dominated (99.5%) by muons. Two high quality tracks, with momentum greater than 5 GeV are required to form a vertex inside the fiducial volume and to be detected by the Charged Hodoscope (CHOD) downstream of the tracking system. The CHOD provides the reference timing with $\sim$200-300 ps resolution. Events with activity in time with the two tracks in the main NA62 veto detectors have been removed. Two main background components have been identified:

- *Combinatorial background:* A dangerous source of background comes from random combinations of tracks from the muon halo which enter the decay volume and mimic signal events.

This background does not point backward to the dump, forms a vertex with a poor quality, and has the two tracks mostly non coincident in-time, as the halo muons are uniformly spread along the 3.5-sec long spill;

- *Neutrino- and muon-induced backgrounds:* neutrinos and muons can interact inelastically with the material upstream and surrounding the decay volume. These interactions can generate particles, including V^0, that enter in the decay volume and mimic signal events. While K_S and Λ typically decay within the first 5 m of the decay volume, the K_L or random combination of tracks from the inelastic interactions can simulate a signal appearing as an isolated vertex in the decay volume. This background does not point backwards to the dump and is mostly vetoed by the veto systems.

Overall 28 events of the opposite-charge category are left after the selection, fully dominated by the 2-muon sample. A powerful handle to further reduce the background while searching for fully reconstructed signal final states (eg: $HNL \to \pi^{\pm} l^{\mp}$ with $l = \mu, e$; Dark Photon or Dark scalar $\to f^+ f^-$, with $f = e, \mu, \pi, K$) is to require the events to point backwards to the dump: as expected, all the events from the analyzed data sample do not satisfy this condition and can be removed by a mild cut in impact parameter.

However, also most of the HNLs' decays do not point backwards to the dump, as they contain along with the 2-tracks, also photons and neutrinos in the final state that are not detected (eg: $HNL \to \pi^{\pm}\tau^{\mp}$; $HNL \to l^+ l^- \nu$ or $\rho^{\pm} l^{\mp}$, with $l = e, \mu, \tau$ and $\rho^{\pm} \to \pi^{\pm}\pi^0$ and $\tau \to 1$ prong X). Generic models of asymmetric Dark Matter [68], with $A \to \chi_1 \chi_2$, and $\chi_2 \to f^+ f^-$ also contain partially reconstructed final states.

To control the background for partially reconstructed decay modes, and consolidate the rejection for fully reconstructed ones, namely in the $\mu^+\mu^-$ sample, it is mandatory to add a veto at the entrance of the decay vessel: the extrapolation of the residual background tracks at the entrance of the decay vessel (Figure 4, left) shows that the remaining background is concentrated in the zone that can be covered by an Upstream Veto (Figure 4, right).

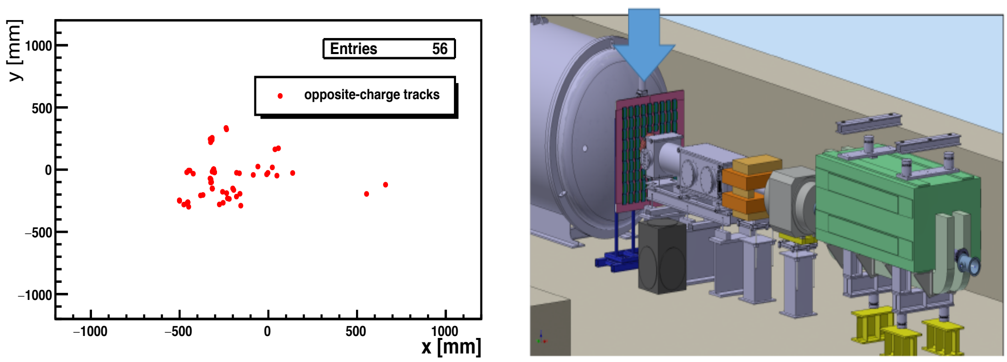

Figure 4: Left: Transverse illumination of muons from the $\mu^{\pm}\mu^{\mp}, e^{\pm}\mu^{\mp}$ selected pairs at the entrance of the decay vessel. Right: conceptual design of the Upstream Veto in front of the NA62 decay vessel.

5. Conclusions

NA62 is successfully running in the North Area of the CERN SPS with the main goal of measuring the $BR(K^+ \to \pi^+ \nu\overline{\nu})$ with 10% accuracy. Data collected so far [59] show that an accuracy of ∼20% can be reached in the current run (2016-2018). Owing to the high beam energy and high beam intensity, the long decay volume and the hermetic detector coverage, NA62 also has the opportunity to directly search for a plethora of hidden-sector particles, both in visible or invisible final states.

A large variety of searches for hidden sector particles can be already performed in beam mode using kaon decays and an even broader and richer physics programme can be proposed for the 2021-2023 data taking, including $\sim 10^{18}$ pot (∼80 days) in dump-mode while the large majority (∼85%) of the beam time will be dedicated to kaon physics. Preliminary studies with data taken in beam and beam-dump modes show that the background can be kept under control for most of the decay channels with 2-track final states when an Upstream Veto is added to the current setup.

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