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NA62 results on Dark Sector searches

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Abstract

NA62 is a precision physics experiment studying charged kaons and their decay products with an unprecedented accuracy (measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio of the order of 10^{-11}), allowing indirect probes of new physics scales up to $\mathcal{O}(100)$ TeV. NA62 experiment also searches directly for weakly interacting particles of up to $\mathcal{O}(100)$ MeV masses in kaon decays and up to $\mathcal{O}(1)$ GeV masses when running in the beam dump mode. For both modes of direct searches, NA62 has been collecting data since 2021 after a successful 2016-18 run 1. Past results and future prospects are presented in this talk.

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1 Introduction

Fixed-target experiments can probe regions in the parameter space (m_X, C_X) of New Physics (NP) particle mass m_X and coupling C_X to the Standard Model (SM) particles complementary to those probed by the collider experiments operating at the so-called energy frontier that directly probe mass scales of $\mathcal{O}(1)$ TeV. Fixed-target experiments operate at smaller centre of mass energies but can collect very large statistics while keeping the backgrounds under control, the so-called intensity frontier. At the intensity frontier, very large mass scales ($\gtrsim 100$ TeV) can be probed indirectly, through precision measurements of the SM processes and searches for SM-forbidden decays, and smaller mass scales ($\mathcal{O}(1)$ MeV to $\mathcal{O}(1)$ GeV) can be probed directly[1] for very small NP-SM couplings C_X. This summary will discuss the *direct* searches for NP particles for m_X and C_X values particularly interesting for models describing hypothetical mediators between Dark Matter and Standard Model particles, collectively called the Dark Sector portals. As well as providing an interaction between the SM and the DM sector, these mediators can often provide an explanation of some observations not described by the SM (e.g. neutrino masses, SM mass hierarchy, etc.).

The following table summarizes four portals that appear frequently in the literature and that are targeted as the main benchmark scenarios by the Physics Beyond Colliders initiative [1]. Details of the fields and coupling constants involved will be given in dedicated sections.

Table 1: *Dark Sector portals.*

NP Particle	type	Dark Sector portal (dim ≤ 5)
HNL[2](N_I)	fermion	$F_{\alpha I}(\bar{L}_\alpha H)N_I$
dark photon (A'_μ)	vector	$-\dfrac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
dark Higgs (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$
axion/ALP[3](a)	pseudoscalar	$\dfrac{C_{aX}}{\Lambda}aX_{\mu\nu}\tilde{X}^{\mu\nu}, \dfrac{C_{af}}{\Lambda}\partial_\mu a\bar{f}\gamma^\mu\gamma^5 f$

[1]By direct searches we mean the search for the production of NP particles in SM decays or NP particle decays into SM particles.

These new states can be searched for directly at fixed-target facilities in two types of processes:

- Search for the decay of a NP particle into SM final states seen by the detector, which allows the reconstruction of the original NP particle;
- Search for the decay of a SM particle into SM and NP particles where the NP particles can by reconstructed from the knowledge of the SM initial and final states even if the NP particle does not decay back to SM final states and escapes detection.

The following sections will describe the search for the four Dark Sector portal particles in both types of searches at the NA62 experiment.

2 NA62 experiment

The NA62 experiment is a fixed-target experiment at the CERN North Area and is served with a 400 GeV/c proton beam from the SPS. NA62 is a multi-purpose experiment covering a broad kaon and beam-dump physics programme with the main goal of the measurement of the branching ratio of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay with 10% precision. About 4×10^{12} kaon decays have been collected during the data-taking period 2016-2018 (Run 1) and the result of the corresponding $\mathcal{B}_{K^+\to\pi^+\nu\bar{\nu}}$ measurement is $\mathcal{B}_{K^+\to\pi^+\nu\bar{\nu}} = (10.6 \pm 4.0) \times 10^{-11}$ [2]. Data-taking resumed in 2021 (Run 2) after the CERN Long Shutdown 2 (LS2).

2.1 Kaon mode

In standard data-taking mode, called the *kaon mode*, the 400 GeV/c proton beam impinges on a beryllium target, producing a secondary beam from which a 75 GeV/c component is selected using movable copper-iron collimators called TAXes, located about 23 m from the target. The 75 GeV/c secondary beam has a $\sim$ 750 MHz particle rate and consists of about 6% K^+. The kaons in the beam are selected using a Cherenkov counter detector (KTAG), which also provides the timing for the kaon tracks, while their momenta are measured by a silicon pixel spectrometer (GTK). The particle beam then enters a 117 m

[2]Heavy neutral lepton.
[3]Axion-like particle.

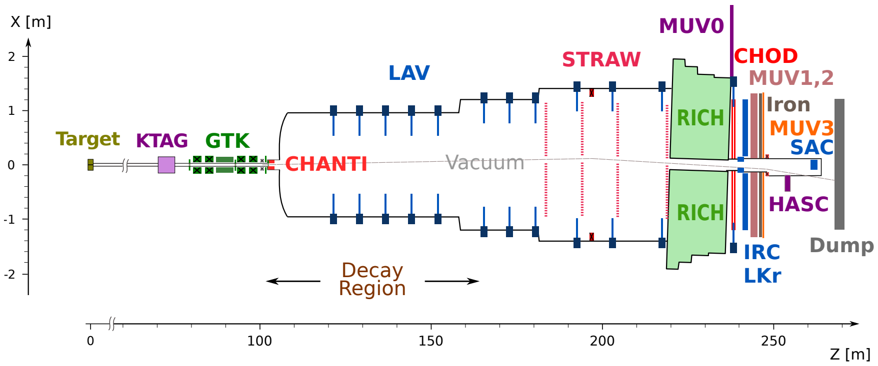

Figure 1: *Schematic layout of the NA62 experiment in the X-Z plane in 2018* [2].

long vacuum vessel where about 14% of the beam kaons decay in the fiducial volume (FV) that occupies the first about 75 m of the vacuum vessel. The momenta of the kaon decay products are measured using the STRAW spectrometer, consisting of 4 straw stations and a 0.9 Tm magnet. The vacuum vessel is followed by a ring-imaging Cherenkov counter (RICH) optimized for the momentum range 15-35 GeV/c, to separate the final state π^+ and μ^+ [5]. Further particle identification (PID) is by a sequence of calorimeters: the electromagnetic calorimeter (LKr) and hadronic calorimeters (MUV1 and MUV2). Muon identification is provided by a scintillating-tile muon detector (MUV3), located behind an 80 cm thick iron wall. The RICH and the charged hodoscope (CHOD) also provide the timing for the tracks of the final state particles.

2.2 Beam-dump mode

The experiment can also operate in a so-called *beam-dump mode* to search for NP particles too heavy to be produced in the kaon decays. In the beam-dump mode, the beryllium target is lifted from the beam line and the TAX collimators are closed, effectively dumping the 400 GeV/c beam. Only neutrinos, muons and hypothetical NP particles produced in the interaction of the beam with the material of the TAX and in secondary particle decays can penetrate the TAX and reach the NA62 decay volume. The currents of a set of dipole magnets, used for the modulation of the beam selected by TAX in the kaon mode, are set to produce magnetic fields in the same direction in the beam-dump mode in order to sweep the muons from the decay volume acceptance since the halo muon flux is the dominant background in the beam-dump mode [3]. The detectors preceding the decay volume are not used in the beam-dump data analyses except for an upstream veto (ANTI0), which allows further reduction of the muon halo background at the analysis level.

Three trigger lines are implemented in beam-dump mode:

1. Control, triggered by total deposited energy in the LKr of above 1 GeV and at least one reconstructed LKr cluster;
2. Q1/20, triggered by at least one signal in CHOD and downscaled by 20;
3. H2, triggered by two in-time signals in different CHOD tiles.

The low particle rate in beam-dump mode allows data to be collected at an increased proton beam intensity (about a factor 1.5 higher than in the kaon mode) resulting in rates of Control, Q1/20 and H2 triggers for the 4, 14 and 16 kHz respectively.

In 2021, data from about 1.4×10^{17} protons dumped on TAX (POT) were collected at NA62 during a period of 10 days of operation in the beam-dump mode. During the whole of Run 2 a total of about $N_{\mathrm{POT}} = 10^{18}$ POT is expected.

3 Search for heavy neutral leptons

The general form of the HNL portal is

$$\mathcal{L} \supset F_{\alpha I}(\bar{L}_\alpha H)N_I, \tag{1}$$

where H is the Higgs doublet, L_α is the left-handed doublet of the SM neutrino of flavour α, N_I is the I-th HNL field and we sum over the flavour indices. Upon breaking the electroweak symmetry and diagonalizing the neutrino mass terms one obtains mixing terms between the neutrinos ν and HNLs L, typically parametrized by elements of matrix U for the respective flavours. Processes involving HNLs can then be obtained from the neutrino processes by an exchange $\nu_\alpha \to U_{\alpha I} L_I$. In the minimal scenario with one HNL, one can express

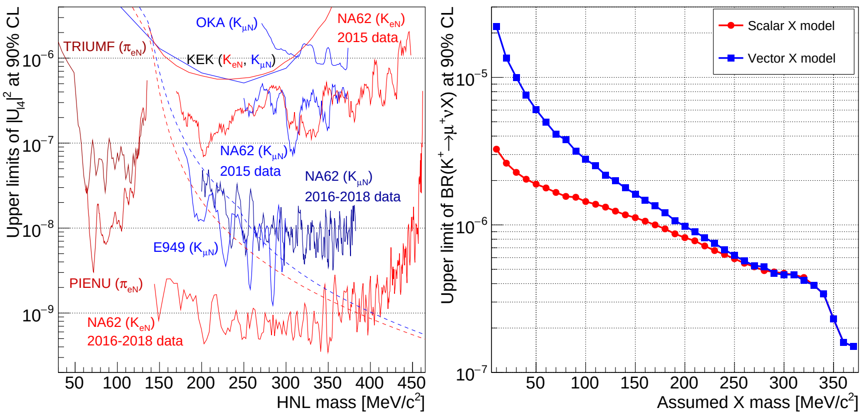

Figure 2: *Left: UL at 90% CL on $|U_{\ell 4}|^2$ from production searches, red: $|U_{e4}|^2$, blue: $|U_{\mu 4}|^2$. Right UL on $\mathcal{B}(K^+ \to \mu^+ \nu X)$, where X is scalar or vector.*

the branching ratio of the HNL production in a decay of a kaon K^+ to a charged lepton l^+ as

$$\mathcal{B}(K^+ \to \ell^+ N) = \mathcal{B}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{l4}|^2, \tag{2}$$

where ρ_ℓ is a kinematic factor.

A search for HNL production in K^+ decays has been performed at NA62 in the Run 1 dataset in two independent analyses: with a muon [6)] and with a positron [7)] in the final state and with the HNL escaping detection.

The strategy of these analyses is to search for a spike in the missing mass spectrum $m^2_{\text{miss}} = (P_K - P_\ell)^2$ that would correspond to the HNL mass m_N. The scan in m_N is performed in steps of $\mathcal{O}(1)$ MeV/c^2 in mass ranges: 144–462 MeV/c^2 for the $K^+ \to e^+ N$ decay and 200–384 MeV/c^2 for the $K^+ \to \mu^+ N$ decay. The upper limits on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ obtained are plotted in Fig.2, left.

The analysis is also re-interpreted as a search for decay $K^+ \to \mu^+ \nu X$, where X is a scalar or vector. The corresponding upper limits on the branching ratios of these two cases, given the mass of particle X, are plotted in Fig.2, right. Another re-interpretation is a search for decay $K^+ \to \mu^+ \nu\nu\bar{\nu}$, where the upper limit obtained on the branching ratio[4] is $\mathcal{B}(K^+ \to \mu^+ \nu\nu\bar{\nu}) < 1.0 \times 10^{-6}$.

[4] The predicted SM branching ratio is of the order 10^{-16}.

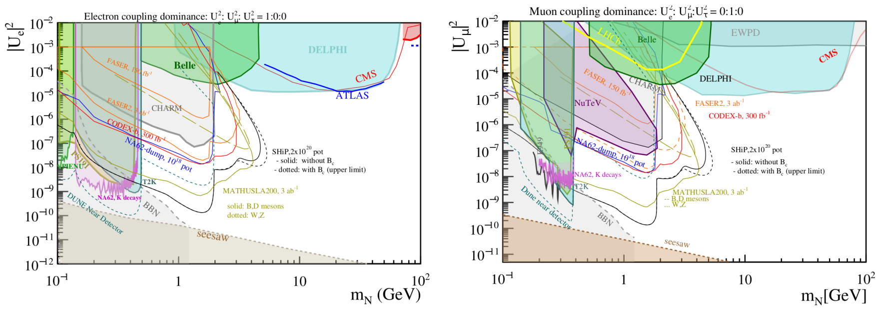

Figure 3: *UL at 90% CL on* $|U_{\ell 4}|^2$ *(left:* $|U_{e4}|^2$*, right:* $|U_{\mu 4}|^2$*) comparison with beam-dump searches. Blue contour: projected NA62 sensitivities at* $N_{\mathrm{POT}} = 10^{18}$ *combining searches for all kinematically allowed decay channels, including channels with open kinematics.*

NA62 is also competitive in searches for HNL with masses ~ 1 GeV with the full statistics that will be collected in Run 2 in the beam-dump mode, see Fig. 3 [8].

4 Search for dark photons

The Dark photon A' is a vector particle corresponding to a new $U(1)$ gauge symmetry. In the "minimal scenario" the dark photon interacts with the SM hypercharge through kinetic mixing term

$$\mathcal{L} \supset -\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}, \tag{3}$$

where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$, $B_{\mu\nu}$ is the SM hypercharge field strength tensor, θ_W is the Weinberg angle and ε is the coupling constant.

Dark photons can be produced through two mechanisms in the beam-dump mode at NA62 in proton-nucleus interactions:

- Bremsstrahlung production: $p + N \to X + A'$;
- meson-mediated production: $p + N \to X + M$, $M \to A' + \gamma(\pi^0)$, where $M \in \{\pi^0, \eta, \rho, \omega, ..\}$.

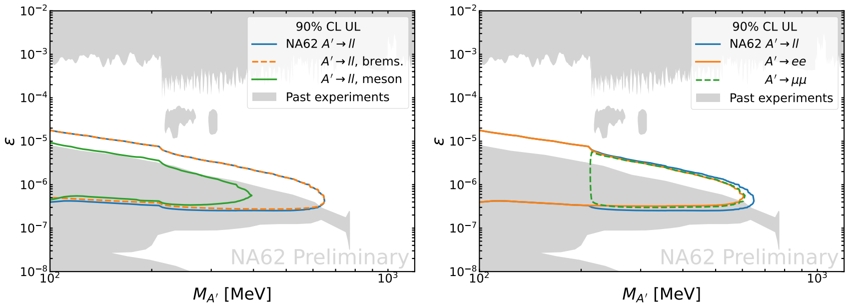

Figure 4: *NA62 sensitivity for dark photons, assuming 0 observed events in* 1.4×10^{17} *POT, per production mechanism (left) and per decay mode (right).*

The two mechanisms differ cross-sections and the angle-momentum distribution of the radiated dark photons, see NA62 sensitivity in Fig. 4 left. For dark photon masses $M_{A'} < 700$ MeV, the decay width is dominated by the lepton-antilepton decays, see Fig. 4 right. The expected dark photon yield $N_{\rm exp}$ is given by

$$N_{\rm exp} = N_{\rm POT} \times \chi(pp \to A') \times \mathcal{B}(A' \to \ell^+\ell^-) \times P_{RD}(\varepsilon) \times A_{\rm acc} \times A_{\rm trig}, \quad (4)$$

where $\chi(pp \to A')$ is the dark photon emission probability, $\mathcal{B}(A' \to \ell^+\ell^-)$ is the branching ratio, P_{RD} is the probability to decay in the NA62 decay volume and $A_{\rm acc}$ ($A_{\rm trig}$) is the signal selection (trigger) efficiency.

A search for dark photon decays to a $\mu^+\mu^-$ pair has been performed at NA62 with a sample with $N_{\rm POT} = 1.4 \times 10^{17}$ selected using the H2 trigger in the beam-dump mode. The strategy of this analysis is to find the secondary $\mu^+\mu^-$ vertex in the decay volume and reconstruct the primary vertex as a point of closest distance of approach of the reconstructed A' track to the proton beam. The primary vertex is expected to lie near the beam impact point on the TAX, see Fig. 5 left. Signal and control regions (SR, CR) are selected as $\pm 3\sigma$ in each axis of the expected signal distribution and are kept blinded in the data until the analysis is finalized.

The selection criteria are 2 tracks of opposite charge in coincidence in time with the trigger and with each other. The particle identification requires

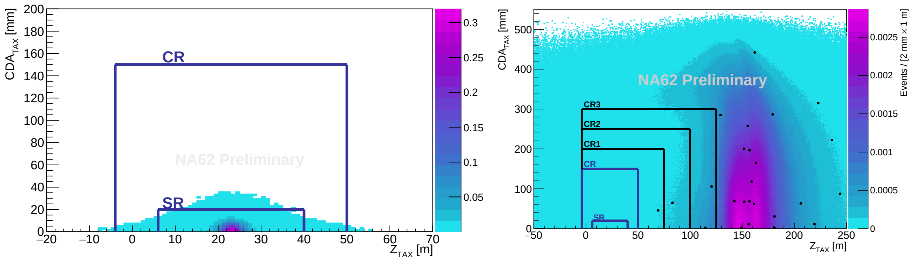

Figure 5: *Left: Signal MC and definition of control (CR) and signal regions (SR). Right: Data-MC comparison, SR closed.*

a single hit in MUV3 for each track and a ratio of energy deposited in the LKr and momentum $E/p < 0.2$. Additionally, no in-time activity in the LAV is allowed to reduce the background from secondary interaction of halo muons.

After applying the LAV veto, the dominant source of background is due to a random pairing of two halo muons from interactions of uncorrelated protons. To evaluate this background a control sample selected with the Q1 trigger in the absence of H2 has been used. See Fig.5 right and Tab. 2 for the comparison of the number of expected and observed background events.

Table 2: *Summary of expected $\mu^+\mu^-$ events from combinatorial background (N_{exp}), the related uncertainty (δN_{exp}), the observed events in data (N_{obs}) and the probability to obtain a likelihood L for data-MC compatibility equal or worse than that corresponding to N_{obs} ($P_{\mathrm{L} \leq \mathrm{L_{obs}}}$).*

	$N_{\mathrm{exp}} \pm \delta N_{\mathrm{exp}}$	N_{obs}	$p_{N \geq N_{\mathrm{obs}}}$	$p_{L \leq L_{\mathrm{obs}}}$
outside CR	26.3 ± 3.4	28	0.41	0.74
CR3	1.70 ± 0.22	2	0.25	0.25
CR2	0.58 ± 0.07	1	0.44	0.44
CR1	0.29 ± 0.04	1	0.50	0.68
CR1+2+3	2.57 ± 0.33	4	0.26	0.24
CR	0.17 ± 0.02	0	1.0	1.0
SR	0.016 ± 0.002	-	-	-

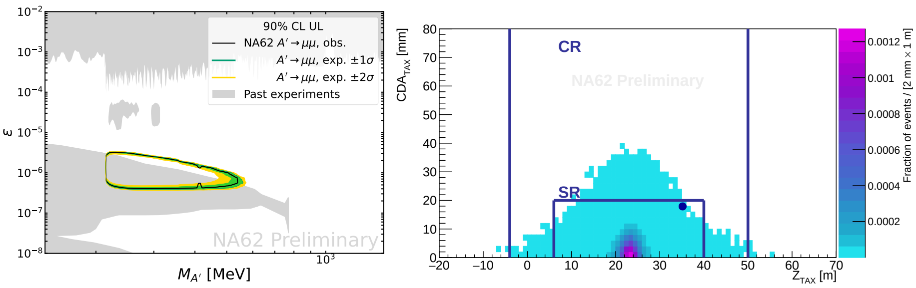

Figure 6: *Left: Final result with upper limit at* 90% *CL. Right: Signal MC - data, 1 event observed - counting experiment with* 2.4σ *significance. Signal shape not taken into account for the significance.*

No events have been observed in the CR. After opening the SR, one event with invariant mass ~ 411 MeV has been found. The corresponding upper limit at 90% CL is the region enclosed by black contour in Fig. 6 right. As a counting experiment, the global significance of the event observed is 2.4σ. Note, however, that the track time difference is about two standard deviations from the value of zero expected for in time tracks and that the extrapolation of the corresponding track to the impact point is barely in the SR, see Fig. 6 right, suggesting that the event found could be a combinatorial background event.

5 Search for axion-like particles

Axions were originally predicted as a possible explanation of the CP conservation in strong interactions, called the Strong CP problem. A more general case with various possible couplings to the SM not necessarily addressing the strong CP problem (axion-like particle/ALP) is usually considered:

- SM gauge boson coupling: $\mathcal{L} \supset \dfrac{C_{XX}}{\Lambda} a X_{\mu\nu} \tilde{X}^{\mu\nu}$, $X \in \{B, W, G\}$;
- SM fermion coupling: $\mathcal{L} \supset \dfrac{C_{ff}}{\Lambda} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$, $f \in \{q, \ell\}$.

If one of the ALP-SM couplings, C_{qq}, C_{gg}, C_{WW} is non-zero ALPs can be produced in flavour-changing neutral current decays, such as $B \to K^{(\star)} a$ and

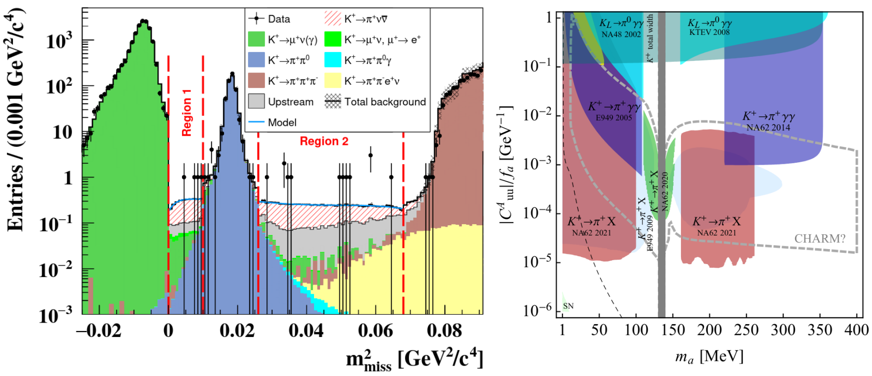

Figure 7: *Left: Expected and observed number of $K^+ \to \pi^+\nu\bar{\nu}$ events as a function of the reconstructed m^2_{miss} for the 2018 data set* [4]*. Right: Bounds on flavor-diagonal pseudoscalar quark couplings: coupling of ALP to up quarks* [9]*.*

$K \to \pi a$. Since the decay $K^+ \to \pi^+ a$ would have the same signature as the $K^+ \to \pi^+\nu\bar{\nu}$ decay, it would appear as a peak above the continuous missing invariant mass spectrum of the $K^+ \to \pi^+\nu\bar{\nu}$ decay, see the $K^+ \to \pi^+\nu\bar{\nu}$ spectrum in 2018 NA62 data in Fig. 7 left. See Fig. 7 right for the upper limit obtained on the exclusion in the parametric space (m_a, C_{uu}) for the case of an ALP coupling to SM up-quarks based on the NA62 Run 1 data.

Depending on the coupling of ALPs to the SM, ALPs can be produced in the TAX in the beam-dump mode in various ways:

- photon-mediated (Primakoff) production from both off- and on-shell photons [10, 11];
- flavour-changing neutral current B meson decays [12];
- through mixing with other neutral pseudoscalars (π^0, η, η') [13];
- interaction of secondary muons with the TAX nuclei [14].

NA62 is sensitive to various decay channels (di-photon, di-lepton, hadronic) of ALPs of masses and couplings that have not yet been probed by other experiments, see Fig. 8 left for photonic coupling and right for gluonic coupling.

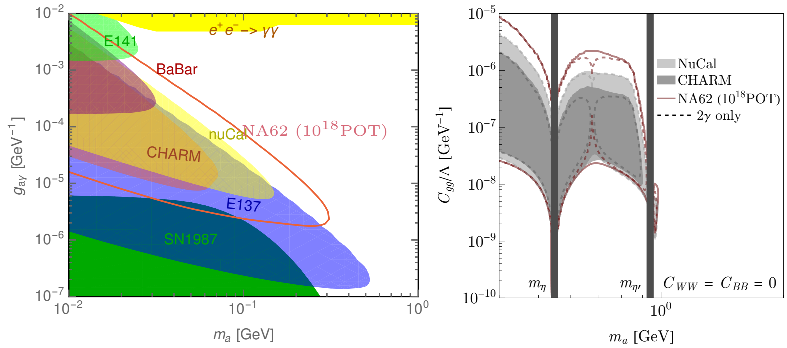

Figure 8: *NA62 Run 2 sensitivity with respect to past exclusions. Left:* $a \to 2\gamma$ *search for* $g_{a\gamma} = C_{\gamma\gamma}/\Lambda$ *coupling scenario* [11]. *Right:* $a \to$ *hadrons and* $a \to 2\gamma$ *search for* C_{gg} *coupling-only* [13].

6 Search for dark scalars

In the minimal model, a dark scalar S is coupled to the SM Higgs boson through the $H^\dagger H$ operator as

$$\mathcal{L} \supset -(\mu S + \lambda S^2) H^\dagger H. \tag{5}$$

Below the electroweak symmetry breaking scale H is substituted by $(v+h)\sqrt{2}$ and non-zero coupling μ would lead to mixing between S and h, which can be parametrized for small μ as

$$\theta \simeq \theta = \frac{\mu v}{m_h^2 - m_S^2}, \tag{6}$$

where $v = 246$ GeV.

At loop level, the dark scalar can be produced in flavour-changing neutral current processes and therefore, as in the case of ALPs, would appear at NA62 in the kaon mode as a bump above the $K^+ \to \pi^+ \nu\bar{\nu}$ spectrum. See Fig. 9 left for the exclusion in the $(m_S, \sin\theta)$ parametric space, corresponding to the full Run 1 statistics.

In the NA62 beam-dump mode, dark scalars can be produced in decays of secondary B mesons produced in the TAX. With the full Run 2 beam-dump

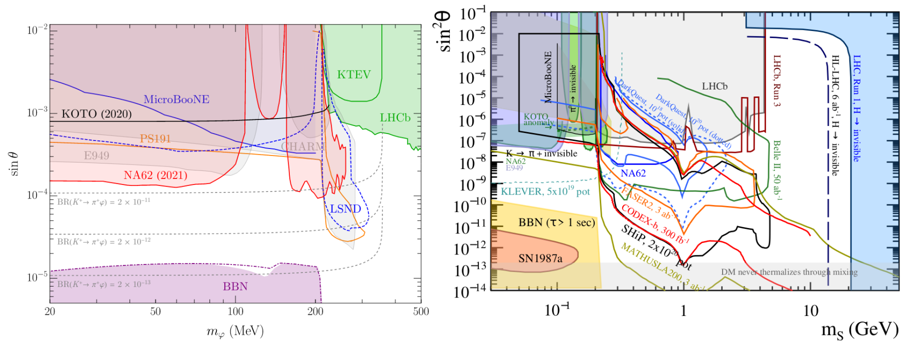

Figure 9: *Excluded regions of* $(m_S, \sin\theta)$ *parameter space for* S *decaying only to visible SM particles. Left: exclusion from* $K^+ \to \pi^+ + inv.$ *and* $\pi^0 \to inv.$ *decays* [9] *(red). Right: Projection for NA62 in the beam-dump mode* 10^{18} *POT* $S \to \mu\mu$ *(blue)* [8].

data sample, NA62 is sensitive in yet unexplored regions of the dark scalar parameter space, see Fig. 9 right, with the dark scalar decays to ee, $\mu\mu$ and $\pi\pi$ pairs.

7 Conclusion

NA62 is a multipurpose experiment that as well as the main goal of $K_{\pi\nu\bar{\nu}}$ and precision measurements, covers a wide program of direct searches for NP particles in both the kaon and beam-dump modes. NA62 results for various Dark Sector benchmark scenarios have been presented, including the first result using the 2021 beam-dump dataset.

NA62 can probe new regions in Dark Sector mass-coupling parameter spaces many years before dedicated facilities are built. Data-taking has been ongoing since since 2021 as a Run 2 with various software and hardware updates and increased beam intensity.

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