Exotic searches at NA62

T. Spadaro([1])(*)

([1]) *Laboratori Nazionali di Frascati INFN, Via E. Fermi 40, 00044 Frascati (Italy)*

Summary. — Very weakly coupled new-physics particles in the MeV-GeV range appear as mediators in various "portals" to a hidden sector. Their interaction with Standard Model particles is feeble and these states are usually long-lived, so that the experimental search fully profits of a high-intensity setup, such as that of fixed-target experiments. The high-intensity setup and detector performance of the NA62 experiment at CERN SPS perfectly adapts to this concept. The status and prospects of such "exotic" searches in the NA62 framework are discussed.

(*) On behalf of the NA62 Collaboration: R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, M. Barbanera, A. Biagioni, L. Bician, C. Biino, A. Bizzeti, T. Blazek, B. Bloch- Devaux, V. Bonaiuto, M. Boretto, M. Bragadireanu, D. Britton, F. Brizioli, M.B. Brunetti, D. Bryman, F. Bucci, T. Capussela, A. Ceccucci, P. Cenci, V. Cerny, C. Cerri, B. Checcucci, A. Conovaloff, P. Cooper, E. Cortina Gil, M. Corvino, F. Costantini, A. Cotta Ramusino, D. Coward, G. D'Agostini, J. Dainton, P. Dalpiaz, H. Danielsson, N. De Simone, D. Di Filippo, L. Di Lella, N. Doble, B. Dobrich, F. Duval, V. Duk, J. Engelfried, T. Enik, N. Estrada-Tristan, V. Falaleev, R. Fantechi, V. Fascianelli, L. Federici, S. Fedotov, A. Filippi, M. Fiorini, J. Fry, J. Fu, A. Fucci, L. Fulton, E. Gamberini, L. Gatignon, G. Georgiev, S. Ghinescu, A. Gianoli, M. Giorgi, S. Giudici, F. Gonnella, E. Goudzovski, C. Graham, R. Guida, E. Gushchin, F. Hahn, H. Heath, T. Husek, O. Hutanu, D. Hutchcroft, L. Iacobuzio, E. Iacopini, E. Imbergamo, B. Jenninger, K. Kampf, V. Kekelidze, S. Kholodenko, G. Khoriauli, A. Khotyantsev, A. Kleimenova, A. Korotkova, M. Koval, V. Kozhuharov, Z. Kucerova, Y. Kudenko, J. Kunze, V. Kurochka, V.Kurshetsov, G. Lanfranchi, G. Lamanna, G. Latino, P. Laycock, C. Lazzeroni, M. Lenti, G. Lehmann Miotto, E. Leonardi, P. Lichard, L. Litov, R. Lollini, D. Lomidze, A. Lonardo, P. Lubrano, M. Lupi, N. Lurkin, D. Madigozhin, I. Mannelli, G. Mannocchi, A. Mapelli, F. Marchetto, R. Marchevski, S. Martellotti, P. Massarotti, K. Massri, E. Maurice, M. Medvedeva, A. Mefodev, E. Menichetti, E. Migliore, E. Minucci, M. Mirra, M. Misheva, N. Molokanova, M. Moulson, S. Movchan, M. Napolitano, I. Neri, F. Newson, A. Norton, M. Noy, T. Numao, V. Obraztsov, A. Ostankov, S. Padolski, R. Page, V. Palladino, C. Parkinson, E. Pedreschi, M. Pepe, M. Perrin-Terrin, L. Peruzzo, P. Petrov, F. Petrucci, R. Piandani, M. Piccini, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, M. Raggi, A. Romano, P. Rubin, G. Ruggiero, V. Ryjov, A. Salamon, C. Santoni, G. Saracino, F. Sargeni, V. Semenov, A. Sergi, A. Shaikhiev, S. Shkarovskiy, D. Soldi, V. Sougonyaev, M. Sozzi, T. Spadaro, F. Spinella, A. Sturgess, J. Swallow, S. Trilov, P. Valente, B. Velghe, S. Venditti, P. Vicini, R. Volpe, M. Vormstein, H. Wahl, R. Wanke, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko

1. – Introduction

Firm cosmological indications exist of a gravitationally-active abundant dark matter (DM). No Standard Model (SM) field satisfies the proporties of DM, as deduced from observational cosmology. If DM has been generated as a thermal relic from the hot early universe, one can hunt for it in particle physics. In particular, the dominance of DM on ordinary matter in the universe might suggest the existence of an entirely new "dark" sector with specific forces and particles fleebly coupled to the SM.

As an example, in a rather general set of hidden sector models with an extra U(1) gauge symmetry [1], the interaction of a dark photons (denoted A') with the visible sector proceeds through kinetic mixing with the SM hypercharge. Such scenarios with GeV-scale dark matter provide possible explanations to the observed rise in the cosmic-ray positron fraction with energy and the muon gyromagnetic ratio $(g-2)$ measurement [2].

NA62 [3] is a fixed target experiment at CERN with the main goal of measuring the BR of the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$ with 10% precision. The SM predicts [4] $\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$, therefore about 10^{13} K^+ decays for a 10% signal acceptance need to be collected. At full intensity, a beam of 10^{12} 400 GeV protons in a 3.5 s long spill from the Super-Proton-Synchrotron (SPS) hit a beryllium target to produce a 75 GeV momentum-selected 750-MHz intense secondary beam of positive particles, 6% of which are charged kaons. Keeping the background to signal ratio to about 10% requires the use of redundant experimental techniques to suppress unwanted final states. Fig. 1 shows a schematic view of the NA62 experimental apparatus [3]. NA62 has been designed and built requiring high intensity, full particle identification, hermetic coverage and low material badget, high rate tracking.

2. – The NA62 experimental apparatus

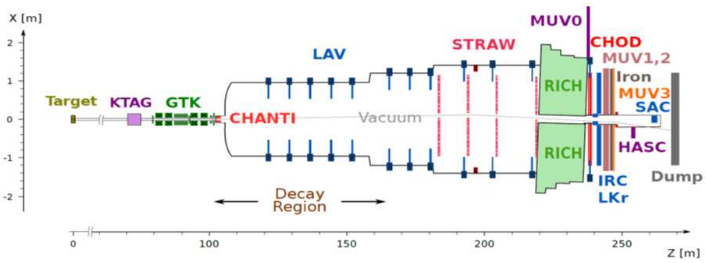

Fig. 1. – Scheme of the NA62 experimental apparatus

Primary SPS protons hit a berillium target from which a secondary charged hadron beam of 75 GeV/c is selected and transported to the decay region, more than 100 m downstream the target. Incoming kaons are positively identified by a differential Cerenkov counter (KTAG). This particle-ID information can be time-matched with the measurements of momentum and direction of each charged particle in the beam, which are provided by an achromat system hosting three stations of Si-pixel detectors (GTK). Kaon decays in a ~ 60 m long sensitive volume in a 10^{-6} mbar vacuum can be reconstructed: the momentum of daughter particles is measured by a spectrometer made of a

~ 270 MeV-P_T-kick bending magnet and 4 straw-based chambers; photons are detected by an hermetic system made of two small angle calorimeters in the very-forward region (IRC and SAC), an electromagnetic calorimeter based on liquid krypton (LKr) in the forward region, and lead-glass annular calorimeters (LAV) if emitted at large angle. The total rejection capability for a π^0 of energy above 40 GeV is at 10^8. A RICH identifies secondary charged pions; plastic scintillators (CHOD) are used for triggering and timing. Hadron calorimeters (MUV1,2) and a plastic scintillator detector (MUV3) placed downstream an iron-based absorber are used to detect hadrons and muons. The overall μ-*versus*-π rejection in the chosen signal momentum range, between 15 and 35 GeV/c, is at 10^7. Information from CHOD, RICH, MUV3 and LKr are hardware processed to issue level zero trigger conditions up to 1 MHz bandwidth. Software-based algorithms from KTAG, CHOD, LAV and STRAW information provide tigher higher level trigger requirements, reducing the rate by a factor of 100. Low-intensity data have been taken in 2015 to study detector performances and to perform physics analysis. Since 2016, NA62 is collecting data for the measurement of the BR($K^+ \to \pi^+ \nu\bar{\nu}$) and other physics goals.

Such setup is suited for a number of exotics searches.

3. – Search for exotic particles from Kaon decays

A large variety of searches for hidden sector particles can be performed at NA62 using its high-intensity kaon beam. By-products of the main physics case are the search for a axion-like particle (a) from the decay $K^+ \to \pi^+ a$ and for a dark scalar from the decay $K^+ \to \pi^+ S$. In both cases, one assumes that the new-physics particle decays to invisible particles or escape detection being long-lived and faintly interacting with the SM fields. In a similar fashion, heavy neutral leptons (N) have been searched in the decays $K^+ \to \mu^+/e^+ N_{\mu/e}$, by exploring the region of positive missing mass hunting for peaks. Data from 2007 (with the same apparatus of the NA48/2 experiment) corresponding to $\sim 10^7$ $K^+ \to \mu^+\nu$ decays have been used to explore the leptonic muon mode [5]. Minimum-bias triggered data from 2015 equivalent to $\sim 3 \times 10^8 K^+$ decays have been used to explore both leptonic modes [6]. No signal has been observed and upper limits have been placed, improving the sensitivity with respect to previous experiments for both the electron and muon modes, see fig. 2.

A search for invisible decays of a dark photon (A') in the decay chain $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma A'$ has been performed using 1.5×10^{10} K^+ decays, corresponding to about 5% of the dataset collected in 2016. Events with a single downstream track reconstructed in the STRAW spectrometer are selected within the same trigger stream used for the $K^+ \to \pi\nu\nu$ decay. The downstream track is required to match in time and space a GTK track, forming a vertex in the fiducial volume of the experimental apparatus and the GTK track is identified as a K^+ by the KTAG detector. The RICH and the calorimeter system allow identification of the downstream track as a pion. The missing mass obtained from the momentum of the downstream and GTK tracks is required to be around the π^0 mass peak. Events with a single photon cluster in the LKr calorimeter are selected. No activity in time with the selected events in LAV, IRC and SAC detectors is required. Given the kaon, pion, and photon momenta, the squared missing mass $M^2_{mass} = (P_K - P_\pi - P_\gamma)^2$ is expected to peak around the A' mass for the $\pi^0 \to \gamma A'$ decay and around zero for the background process $\pi^0 \to \gamma\gamma$ decays with one photon undetected. A data-driven background estimate, based on the tail with negative missing mass values, is used. For each A' mass, the signal region is defined as a 1.5-standard deviation range around the expected invariant mass peak. Frequentistic 90% CL intervals have been determined,

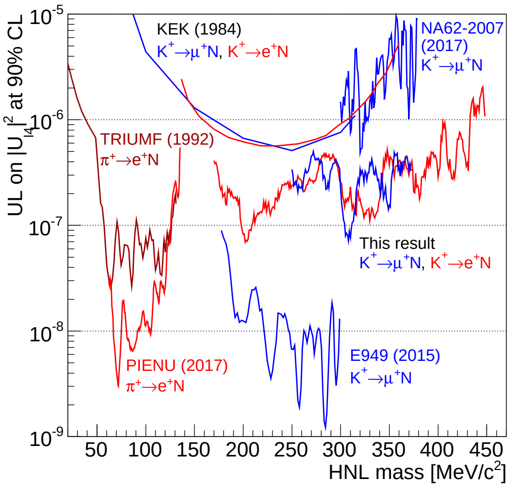

Fig. 2. – 90% CL exclusion limit in the plane of coupling ($|U_l4|^2$) *versus* mass m_N from various pion and kaon leptonic modes. The limits from TRIUMF [7], PIENU [8], KEK [9] and E949 [10] are also shown together with the results from NA62 data taken in 2007 [5] and 2015, labelled as "this result" [6].

taking into account the uncertainties of signal efficiency from MC determination, and the statistical uncertainties of data counts and background expectations. No statistically significant excess has been detected and upper limits have been computed on the number of signal events. The 90% confidence level exclusion limit on the kinetic mixing parameter *versus* the mass of the dark photon is shown in fig. 3 together with the limits from BaBar [11], NA64 [12] and E949 [13] experiments.

4. – Search for exotic particles in NA62 beam-dump mode

Feebly-interacting exotic particles can be originated also by the decay of beauty and charm hadrons, mesons and virtual photons produced in the interaction of protons with a dump. Their couplings to SM particles are very suppressed leading to expected production rates of 10^{-10} or less. Since in this energy range the charm and beauty cross-sections steeply increase with the energy, a high-intensity, high-energy proton beam is an advantage: the 400 GeV/c primary proton beam line serving the NA62 experiment can produce high intensity fluxes of beauty and charm hadrons: 10^{18} POT per nominal year correspond to an order of 10^{15} $D_{(S)}$ mesons, 10^{14} kaons, and 10^{18} $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ mesons in the approximate fractions 6.4/0.68/0.07/0.03/0.94/0.95.

The beryllium target used by NA62 is followed by two 1.6 m long, water-cooled, beam-defining copper collimators (TAX) which can act also as a dump ($\sim$ 10.7 nuclear interaction lengths). In the standard NA62 operation, roughly 50% of the beam protons punch through the beryllium target and are absorbed by the TAX collimators. The simplest experimental signatures of hidden sector visible decays into SM particles correspond to two opposite-charge tracks or two photons originating from the same point of the decay volume (usually displaced from the beam line) and no additional activity in the detector.

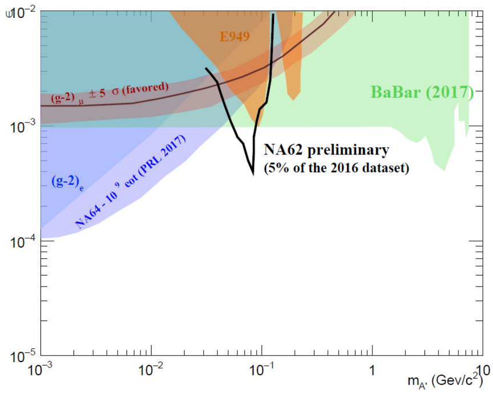

Fig. 3. – 90% CL exclusion limit in the ϵ versun $m_{A'}$ plane for $\pi^0 \to \gamma A'$ events with A' decaying into invisible final states. The limits from BaBar [11], NA64 [12] and E949 [13] are also shown together with the region of the parameters that could explain (g-2)$_\mu$ anomaly (red band) and the region excluded by the agreement of the anomalous magnetic moment of the electron (g-2)$_e$ with the expectations (dark blue shaded area).

Dark photons, for example, can be produced in decays of mesons created in the beam dump, assuming the A' is coupled to quarks, or in hard Bremsstrahlung from the beam protons. NA62 can search for visible decays of A' to e^+e^- and $\mu^+\mu^-$ pairs and other final states. Fig. 4 shows the expected sensitivities assuming 10^{18} protons on target (equivalent of 1 year of running) and zero background for the search of dilepton vertices. The sensitivity takes into account the trigger efficiency and detector acceptance. NA62 could be sensitive to even larger phase space than shown, since in the estimate in

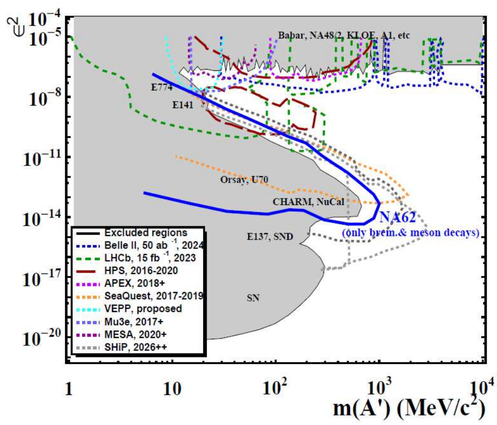

Fig. 4. – NA62 sensitivity (90% CL exclusion limit) for 10^{18} proton on target in the coupling *versus* mass plane for dark photon (blue solid line) originated by the dump.

fig. 4 only production in the beryllium target is considered and not in the TAX. Trigger lines have been designed to acquire multi-track final states in parasitic mode during the standard data taking. A total of $\sim 3\times10^{17}$ (5×10^{16}) POT have been acquired to search for di-muon (electron-positron) modes and are being analyzed. During the 2016 runs, NA62 collected several hours of data at different intensities with the beryllium target lifted from the beam and closed TAX. The collected data is used for feasibility studies and tests of the zero background hypothesis. A preliminary analysis of a fraction of data indicates that a zero-background condition might be achievable [14].

Other physics cases similarly under study concern the search for visible decays of dark scalars, heavy neutral leptons. The expected sensitivity for dark scalars and heavy neutral leptons after collection of 10^{18} POT and assuming zero background are shown in fig. 5 and 6, respectively.

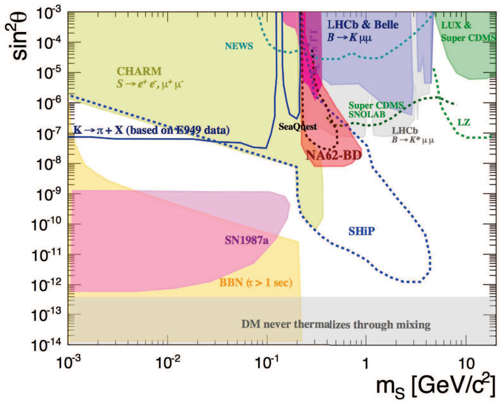

Fig. 5. – NA62 sensitivity (red region labelled as "NA62-BD" corresponding to a 90% CL exclusion limit) for 10^{18} proton on target in the coupling *versus* mass plane for a dark scalar [15] originated by the dump.

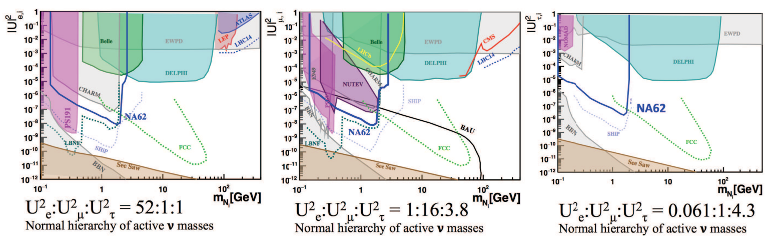

Fig. 6. – NA62 sensitivity (90% CL exclusion limit) for 10^{18} proton on target in the coupling *versus* mass plane for a three theoretical scenarios of heavy neutral lepton models [16], corresponding to the highest possible couplings to electrons (left panel), muons (central panel), and taus (right panel) and normal neutrino hierarchy.

The search for axion-like particles decaying to two photons is peculiar, since it can be pursued solely using a beam-dump setup. The explored production mechanism is the Primakoff [17]. The related analysis of 5×10^{15} POT taken in 2017 is in progress. The expected sensitivity in the zero-background scenario after collection of 10^{18} POT is shown in fig. 7.

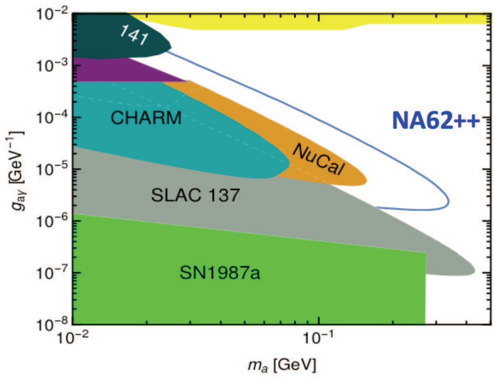

Fig. 7. – NA62 sensitivity (90% CL exclusion limit indicated as NA62++) for 10^{18} proton on target in the coupling *versus* mass plane for an axion-like particle new-physics scenario with photon-coupling dominance [18]. Previous results from electron and proton beam-dump experiments are shown. The bottom region has been excluded after the observation of the supernova SN1987A [19].

5. – Conclusion

NA62 is successfully running in the North Area of the CERN SPS. Owing to the high beam energy and high beam intensity, the long decay volume and the hermetic detector coverage, NA62 has the opportunity to directly search for a plethora of hidden-sector particles, both in visible or invisible final states. Before the LS2 (2018) many searches in the hidden sector will be performed. Recent results on invisible decays of heavy neutral leptons and preliminary results on invisible decays of dark photons were shown. The NA62 collaboration is currently discussing the possibility to use a fraction of the beam time during Run 3 (2021-2023) to operate NA62 in beam-dump mode: this would open a window of opportunity to search for hidden particles. The current NA62 run can be exploited to evaluate background rejection capability up to $10^{17} - 10^{18}$ protons on target.

REFERENCES

[1] Holdom B., *Phys. Lett. B*, **166** (1986) 196.
[2] Pospelov M., *Phys. Rev. D*, **80** (2009) 095002.
[3] The NA62 Collaboration, *JINST*, **12** (2017) P05025.
[4] Buras A.J., *et al. JHEP*, **1511** (2015) 33.
[5] Lazzeroni C., *et al. Phys. Lett. B*, **772** (2017) 712.

[6] Lazzeroni C., *et al. Phys. Lett. B*, **778** (2018) 137.
[7] Britton D., *et al. Phys. Rev. D*, **46** (1992) R885.
[8] Aguilar-Arevalo A., *et al. Phys.Rev. D*, **97** (2018) no.7, 072012.
[9] Yamazaki T., *et al.* Proceedings of the Neutrino 1984 conference.
[10] Artamonov A., *et al. Phys. Rev. D*, **91** (2015) 052001.
[11] BaBar collaboration (J. P. Lees, *et al.*), *Phys.Rev.Lett.*, **119** (2017) no.13, 131804.
[12] NA64 collaboration (D. Banerjee, *et al.*), *Phys. Rev. Lett.*, **118** (2017) no.1, 011082.
[13] E949 collaboration (A. V. Artamonov, *et al.*), *Phys. Rev. D*, **79** (2009) 092004.
[14] Spadaro, T. for the NA62 Collaboration, Talk within the 2016 Physics beyond colliders workshop at CERN (7 Sep. 2016), https://indico.cern.ch/event/523655/timetable/#20160907.detailed.
[15] O'Connell D. and Ramsey-Musolf, M. J. and Wise, M. B., *Phys. Rev. D*, **75** (2007) 037701, Batell, B. and Pospelov, M. and Ritz, A., *Phys. Rev. D*, **83** (2011) 054005, Bezrukov F. and Gorbunov, D., *JHEP*, **05** (2010) 010.
[16] Gorbunov, D. and Shaposhnikov, M., *JHEP*, **10** (2007) . [Erratum: JHEP11,101(2013)].
[17] Dobrich, B., *et al. JHEP*, **1602** (2016) 018.
[18] Jaeckel, J. and Ringwald, A., *Ann. Rev. Nucl. Part. Sci.*, **60** (2010) 405.
[19] Payez, A., *et al. JCAP*, **1502** (2015) no.02, 006.