Study of rare kaon decays at the CERN SPS (NA62)
- 2021 Annual Summary –

1a. Group list (physicists, staff, postdocs, students):

Name	**Position**
Alexandru-Mario BRAGADIREANU	Research scientist (CS III) – IFIN-HH
Stefan-Alexandru GHINESCU	Physicist – IFIN-HH, PhD *Student (Physics)*
Ovidiu-Emanuel HUTANU	Engineer - IFIN-HH*, Master Student (Electronics)*,
Petre-Constantin BOBOC	Physicist – IFIN-HH, *Master Student (Physics)*
Neagu IONEL	Engineer –IFIN-HH
Alina MOTORGA	Accountant- IFIN-HH

1b. Specific scientific focus of group (state physics of subfield of focus and group's role)

Physics: Standard Model

Subfield: Flavor Changing Neutral Current decays with neutrinos in the final state with focus on the measurement of the very rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$ at the CERN SPS (NA62 Experiment).

Group role: Originally, to identify the π^+ coming from the $K^+ \to \pi^+\pi^+\pi^-$ decay (source of background in the $m^2_{miss} \coloneqq (p_K - p_{track})^2$ distribution) with a hadron sampling calorimeter (HASC). The HASC was shown to be efficient also as photon veto in the rejection of background coming from $K^+ \to \pi^+\pi^0$ decay, the upgrade of HASC being proposed in 2018. Evaluation of NA62 sensitivity to various dark matter decays to visible particles. Implementation of various variance reduction techniques in the official Monte Carlo software of NA62.

1c. Highlights of accomplishments in the last year

Concerning HASC upgrade we:

- Installed and commissioned the 9 new HASC modules together with SiPM sensors, front-end electronics and associated services in the NA62 detector chain;
- Replaced the old HASC SiPM sensors – all 90 channels showing high dark current due to the dose accumulated in 2016-2018- and implemented air cooling of old HASC FE electronics, thus improving the performance of the old HASC detector;
- Upgraded the HASC reconstruction software and HASC online monitoring software;

HASC upgrade and commissioning was completed at the end of June, before the starting of 2021 NA62 Physics Run. After that, we maintained the HASC continuous operation during the ongoing NA62 Physics Run and developed a software tool for fast assessing the quality of data acquired by HASC.

At the request of the Exotics Working Group, we postponed the dark scalar related studies and continued the work in the axion like particle (ALP) decaying to a pair of photons. Among other activities, we have developed an algorithm that allows the precise simulation of the most important primary sources of background. This resulted in an ISI paper being published with one of the group members as the first author [13].

2. Scientific goals (2 pages)

The main goal of NA62 experiment [1] is to measure the branching ratio of the ultra- rare kaon decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at the CERN SPS. The standard Model (SM) prediction for the branching ratio is calculated with high precision [2],

$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$$

while significant deviations from the SM value are predicted by new physics models [3,4.5]

In addition to the main objective, thanks to its high beam intensity and detectors performance, NA62 has a wide physics programme: precise measurements of lepton universality in $K^+ \rightarrow l^+ \nu$ decays, searches for Lepton Number (LNV) and Lepton Flavour Number Violating (LFNV) processes and searches for exotic particles such as Dark Photons, Heavy Neutral Leptons, axion-like particles (ALPs), etc. In the framework of Physics Beyond Collider initiative, prospects for data taking in beam dump mode has been addressed too.

In order to reach its main goal, NA62 needs to collect about 100 in-flight $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events, and to keep the total systematic uncertainty small. Assuming a 10% signal acceptance and a $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ branching ratio of 10^{-10}, at least 10^{13} K^+ decays are required.

Since the $\nu\bar{\nu}$ pair is undetectable, the technique adopted by NA62 is to match an upstream K^+ track with a downstream π^+ track and to use the squared missing mass distribution $m^2_{miss} \coloneqq (P_K - P_\pi)^2$ to discriminate the signal from background (Fig. 1). The main background events are expected to come from the other K^+ decay channels and accidental matching of an upstream track with a K^+.

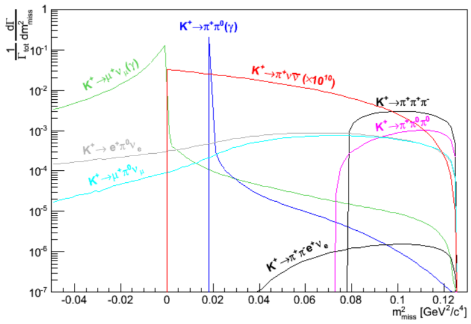


Figure 1: Squared missing mass distribution

2.1 NA62 Hadron Sampling Calorimeter (HASC)

The NA62 experimental setup proposed in the Technical Design Document [7] was improved, by the IFIN-HH team, with a new hadron calorimeter to veto the $K^+ \rightarrow \pi^+\pi^+\pi^-$events in which the π^- undergoes hadronic interaction in the first STRAW chambers and the more energetic π^+ (~40 GeV/c) which is traveling through the beam hole, not being detected by the IRC, then emerging at Z > 253 m.

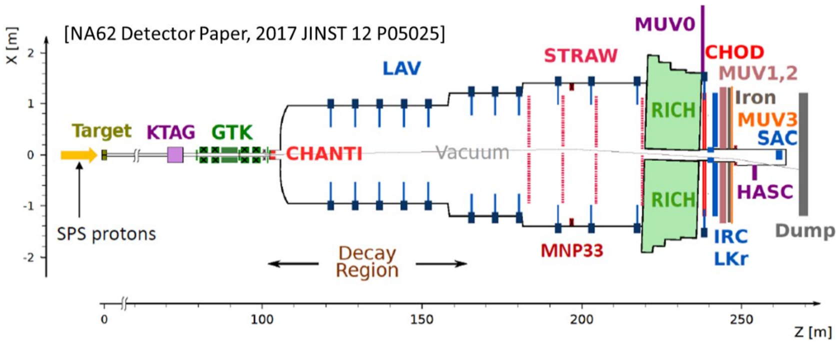


Figure 2: NA62 Experimental setup

Using the data coming from the upstream detectors (Fig. 2) to select the $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays, namely the CEDAR and GTK for K+ identification and the STRAW together with RICH, CHOD and MUV to identify one of the π^+, while HASC has to detect the second π^+ traveling through the beam pipe and deflected by the bending magnet (Fig. 2).

HASC has been demonstrated to be effective (2016-2018 $\pi^+\nu\bar{\nu}$ dataset) as photon veto, complementary to LAV, LKr, IRC and SAC calorimeters, an additional 30 % reduction of $\pi^+\pi^0(\gamma\gamma)$ background being obtained with HASC. This fact, stimulated the idea of using a second calorimeter HASC-like in a position symmetrical with respect to the beam axis, to double the π^0 rejection.

Each HASC station is made up of 9 identical modules recovered from a prototype developed by NA61 Collaboration. Each module is a sandwich of 120 lead/scintillator alternating tiles, with a total volume of 10x10x120 cm^3 (W x H x L). The sampling ratio is 4:1, the scintillator tiles having a dimension of 100 x100 x 4 mm while the lead thickness is 16 mm.

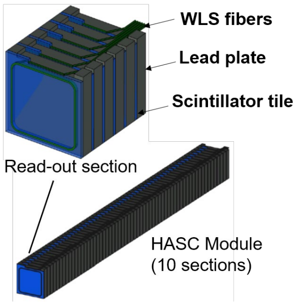


Figure 3: HASC module longitudinal section (left) and optical readout couplings (right)

Each HASC module is organized in 10 longitudinal read-out sections, each scintillator tile of every single section being optically coupled with 1 mm^2 round Wave-Length Shifting (WLS) optical fibers. In the rear side of each module there are 10 optical connectors, originally designed to be coupled with 3x3 mm^2 green sensitive Micro-pixel Avalanche Photodiodes (MAPD), currently S12572-015C Hamamatsu SiPM sensors being used.

The FE electronics and SiPM's installed on the new HASC station, are cooled down to about 21 ºC using a system designed by our group, which consists of 3 Peltier thermoelectric coolers / module and a water-air heat exchanger used to blow cold air in the modules endcap cases. The temperature is maintained constant by a temperature controller – MCU based – which regulates the Peltier supply voltage via a PID routine. Due to last moment mechanical incompatibilities, we were not able in June 2021 to upgrade the old HASC station with new mechanics and Peltier cooling, but we were able to accommodate the cooling with air, which lowered the nominal temperature of SiPM's from 36 ºC to about 24 ºC.

2.2 Study of dark matter

Thanks to its high beam intensity and detectors performance NA62 can achieve sensitivity to new-physics scenarios. Since 2018, IFIN-HH team is actively involved in the study of dark matter in various portals [6]. Our original goal, the study of the Higgs-coupled dark scalar, had to be postponed due to the urgency of finalizing the $ALP \rightarrow \gamma\gamma$ sensitivity evaluation. This search uses data taken in beam dump mode, with 400 GeV/c momentum protons impinging on a 3.2 m long copper/iron block called TAX [7]. The ALP can be then produced via the Primakoff effect and is able to traverse long distances before decaying into a pair of photons [8]. One of the two main background sources has been determined to be photons created in various elements of the NA62 beamline by muons which, in turn, are produced in the TAX in the initial shower. Background events can also come from the decay of K_S and Λ decays. They are predominantly produced by K^+ emerging from the TAX.

The data available for this search amounts to $\sim 1.6 \times 10^{16}$POT and the main goal of our team is to make it possible to simulate a Monte Carlo (MC) sample of size at least 10 times higher than the data. To this purpose, our experience with variance reduction techniques (biasing) has proven to be of paramount importance.

As a follow-up of our work in 2020, various biasing methods have been developed in the NA62 MC framework, helping analyses such as $K^+ \rightarrow \pi^+\pi^0; \pi^0 \rightarrow e^+e^-\gamma$ [9] and $K^+ \rightarrow e^+\nu\gamma(SD^+)$ [10].

3. Scientific achievements in the last three years corresponding to the actual program funding

At the end of 2018 we proposed to the collaboration the upgrade of HASC seeing its success as photon veto. At the request of NA62 collaboration, we performed in 2019-2020 a thorough study on the origin of this additional rejection with the aim of understanding the topology of these events and, consequently to determine the best position for the new HASC modules. The MC revealed that HASC is not hit by the γ from π^0 decay but is sensitive to the e^+ or e^- (Fig. 4) produced in γ pair production. The simulation result, Fig. 5, confirms, as expected, that the veto efficiency is doubled by adding a second calorimeter HASC-like in a position symmetrical with respect to the beam axis.

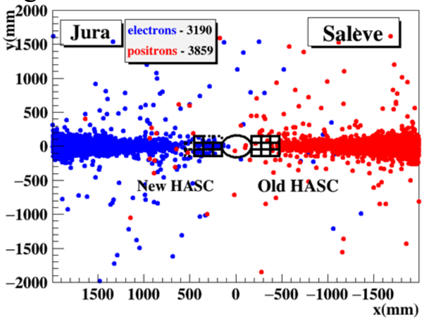


Fig. 4: e^+ e^- distribution at HASC front plane

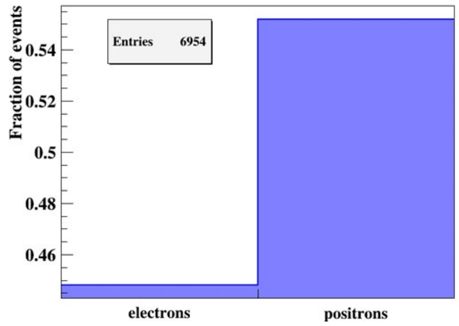


Fig. 5: Fraction of $e^+$and e^- outside HASC acceptance

This evaluation has to be validated by the $\pi^+\nu\bar{\nu}$ analysis, which is still ongoing for the 2021 run.

In 2019 we started the upgrade of HASC by purchasing 9 new HASC like calorimeter modules from NA61 Collaboration. We developed a completely new mechanical structure to support the SiPM sensors and the associated front-end electronics (FEE); we developed a new FEE board for the read-out of 10 SiPM sensors as a substitute of old HASC FEE; we designed and produced a hybrid cooling system based on a water-air heat exchanger and Peltier coolers controlled via a PID routine running on an micro-controller.

5 out of the 9 new HASC modules where tested in IFIN-HH with cosmic rays (Fig. 6), by employing a TDC triggered whenever a HASC section was hit.

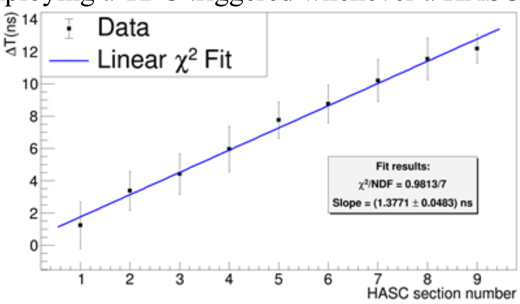


Fig. 6: TOF between successive HASC sections

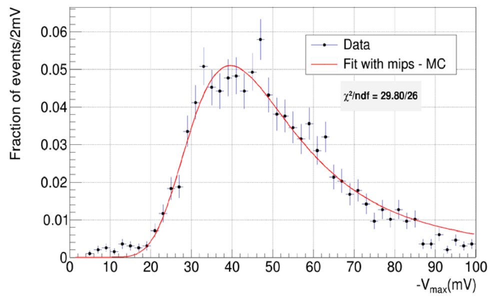


Fig. 7: Signal amplitude / section when all 10 sections are hit

In 2020 we continued the testing of new HASC modules, this time employing a 5 GS /s, 12 bit digitizer. Fig. 7 shows the distribution of SiPM signals when the 10 sections of a HASC module are passed by a cosmic ray muon. The fit with Monte Carlo simulated deposited energy distribution/ section shows good agreement with data.

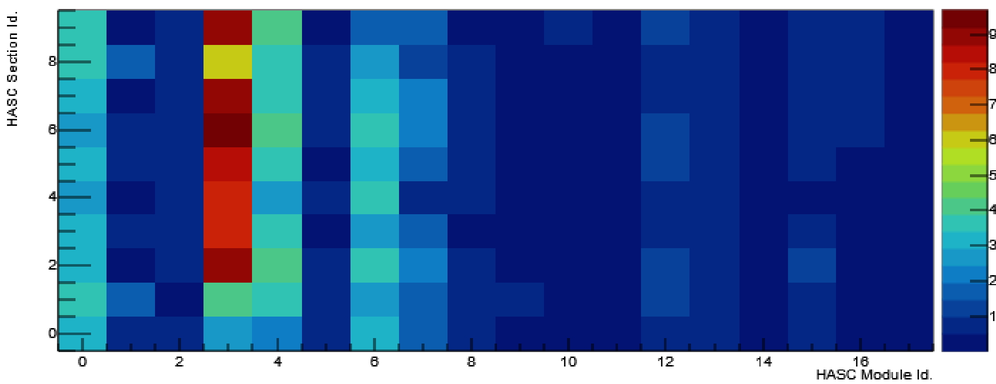


Fig. 8: Screenshot of the 2D hit map used in the Online Monitor of NA62

The installation and commissioning of new HASC was finalized at the end of June 2021. We then updated the Online Monitor tool, which is used during data-taking by shifters in order to ensure a smooth operation. Fig. 8 shows the 2D hit-map with modules 0-8 belonging to the old HASC and 9-17 to the new HASC that is on display at all times during the run.

Up to 2021, the HASC detector performance in NA62 was evaluated by means of a complex selection procedure in which $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays with one π^+ traveling in the beampipe, undetected, were analyzed. However, the 2021 data has been dominated on one hand by large beam fluctuations and on the other hand by instabilities of the GTK detector, which is responsible for the accurate determination of the K^+ momentum. Moreover, the π^+ can never be in the acceptance of the new HASC station, due to the magnet right before the detector. This prompted the idea to study the HASC performance through its response to muons, which is now possible considering the cooling system improves tremendously the SiPM signal characteristics in terms of gain and photon detection efficiency [11].

The muons momentum and position are determined by the STRAW (Fig. 2), together with requiring a MUV3 signal associated both geometrically and in time. Fig. 9 shows the time difference between the muon (MUV3 time) and the closest HASC signal in time. We emphasize that, there is a large improvement in the time resolution of the old HASC, the current time resolution being less than halve with respect to 2018 data, while the time resolution of new HASC is even better due do better cooling.

Since the beam is highly charge-asymmetric, with the majority of the particles being positive, the thresholds on the old HASC ToT boards had to be set higher in order not to congest the TEL62, while for the new HASC, this operation is not needed. Consequently, in Fig. 10, the number of sections fired by an incoming muon has more pronounced peaks at 10 and 20 for the new station, corresponding to 1 and 2 entire modules.

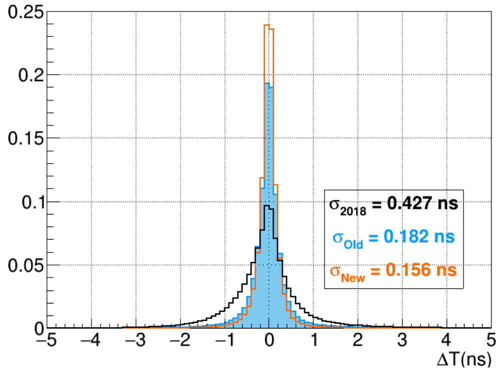


Fig. 9: Muon – HASC time difference, blue for the old station and orange for the new one

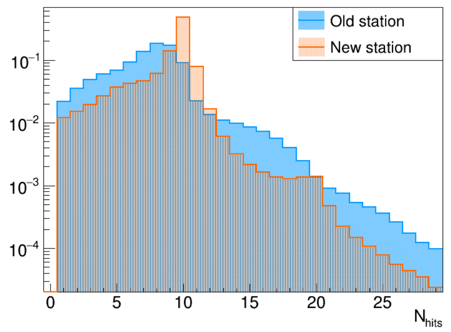
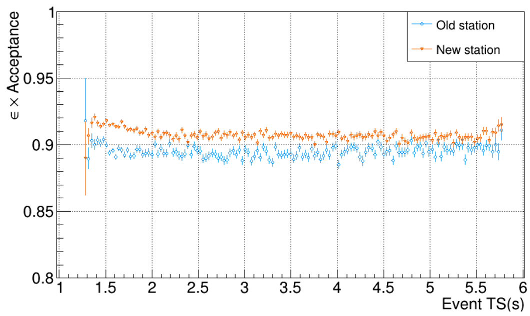


Fig. 10: Number of sections fired by a muon

One of the main problems of the beam in 2021 is a spike in intensity at the beginning of the burst. This has affected most of the NA62 subdetectors. We studied the effective efficiency of the HASC as function of event time stamp. In Fig. 11 we show that neither station experiences a visible drop in efficiency at the beginning of the burst (1.2s-1.5s). Fig. 12 shows that the study with muons can also be used to assess the stability of the HASC through the run.



Fig, 11: Effective efficiency by station, blue for old and orange for new

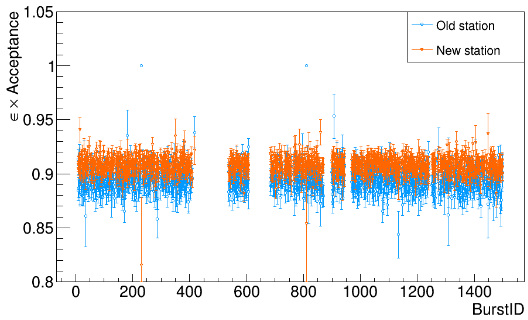


Fig. 12: Effective efficiency by station through a run, blue of old and orange for new

In 2019 we have completed a Toy MC tool for the study NA62 sensitivity to the Higgs-mixed dark scalar (S) in the singlet portal including the associated production mechanism (production by secondaries of beam interactions in TAX). The result was an updated value for the sensitivity enhancement factor by the associated production (1.4 w.r.t 1.7 obtained by SHiP[12]). We have also performed a preliminary background estimation which led to the need of "Shower Libraries" - a large database consisting of detector responses to different kinds of particles (responses taken from full simulations).

In the first months of 2020 we have developed a prototype for the "Shower Libraries" consisting of about 1% of the needed information. We have also devised a software component to retrieve data from the Libraries and fill the missing information in the simulation output. However, due to the latency of random file access in the Libraries, the CPU time gained by not simulating the full event is almost lost.

Searches for possible solutions to the above problem, were halted by the study on HASC photon veto efficiency and, following the success of the biasing technique implemented in that study, a part of the Exotics working group asked our help in implementing a dedicated scheme for their study on Axion-like particles (ALP). ALP is another dark matter candidate for which the NA62 setup and beam dump dataset are competitive at a world-wide scale.

One of the current searches within the experiment focuses on the $ALP \rightarrow \gamma\gamma$ final state and the main sources of background are due to halo muon interactions and K^+ inelastic interactions in the material of the last station of GTK. For the hadronic component, the $K_S \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi^-$ decays are dominant but due to their short life times, only very high momentum particles contribute to this background, but the rate of their production is low. The solution we implemented consisted in the modification of the K^+ inelastic process inside Geant4 to always emit either a K_S or a Λ particle of momentum above 20 GeV/c while correctly accounting for the probability of this to occur. Fig. 13 shows number of interesting events (in light green) is increased by more than 1 order of magnitude in the biased sample. This allowed the group to achieve the needed statistics for background studies.

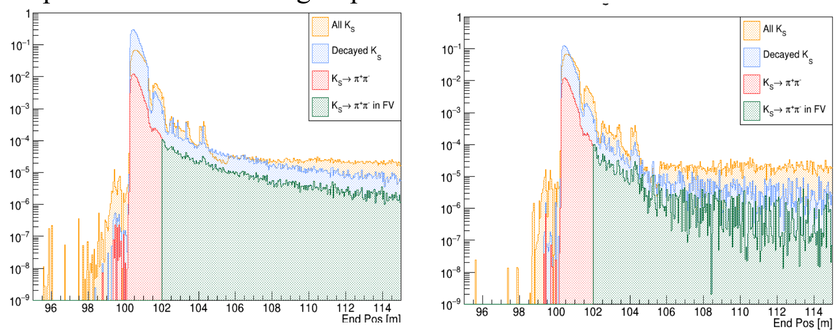


Fig. 13: Decay Z-coordinate of K_S mesons in the biased (left) and standard (right) MC productions

Our second contribution to this search direction involved the μ interactions in the GTK 3 material. Here, the dominant source of background for the ALP search is the production of high energy Bremsstrahlung photons. We have developed a biasing scheme in which muons always produce a high-energy Bremsstrahlung photon (standard rate is ~1%). Finally, we have discovered that a filtering scheme in which the events without high-energy photons were discarded very early in the simulation was more appealing and we have been able to produce the needed MC samples corresponding to $10^{16} POT$.

At the end of 2020 it became clear that the muon halo MC sample the Exotics WG used for this search was inadequate and it had to be redone. They asked for our assistance in providing a means to simulate from first principles a halo corresponding to at least 10^{17}POT. At the beginning of 2021, we devised a biasing algorithm that enables any beam dump setup to produce at least 1 muon per primary proton. The work has been fructified through an ISI publication [13]. Fundamentally, the algorithm allows obtaining an original halo corresponding to $10^{11} - 10^{12}$POT, which can then be oversampled to reach the desired statistics. The results are shown in Fig. 14. Although there is an overall factor missing between data and MC, we note here the abundance of the MC over data, in terms of parameter space. It is also remarkable that the MC sample is capable of reproducing the main qualitative features of the data.

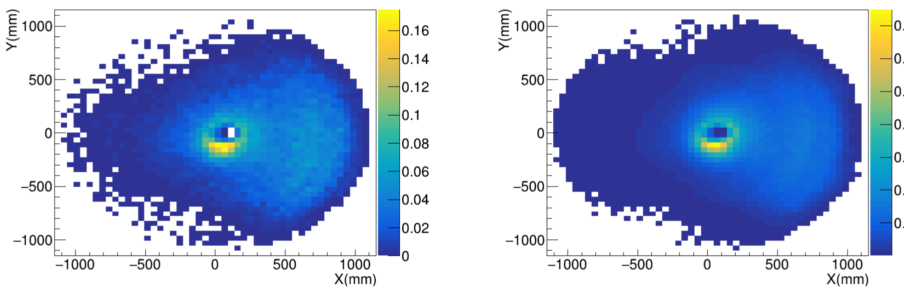


Fig. 14: XY distributions of muons at 180m from the target, data on the left and MC on the right. Color scale indicates number of muons per billion POT.

Thanks to our efforts, we were included on the list of authors for this search. Due to the preparations needed for the 2021 data-taking, the analysis has not been yet finalized, this being expected to happen in the beginning/middle of 2022.

4. Group members (table)

- List each member, their role in project(s) and the % time on each project (analysis, R&D, detector operation, detector construction, etc.)

Name	Role	FTE
Alexandru-Mario BRAGADIREANU	HASC upgrade, maintenance and operation; detector control system; reconstruction software.	0.62
Stefan-Alexandru GHINESCU	Data analysis, MC simulation and reconstruction software	0.67
Ovidiu-Emanuel HUTANU	HASC upgrade, maintenance and operation;	0.58
Petre-Constantin BOBOC	Data analysis	0.68
Neagu IONEL	HASC upgrade and maintenance	0.37
Alina MOTORGA	Project accountant	0.33

- List former students (in last 5 years) and current position/job and institution

  - Victor-Radu Voicu – Programmer, Bit Soft srl, Bucharest
  - Andreea Căluț - Student, Faculty of Physics, Bucharest University

5. Papers and talks in last year

5.1 Papers:

- E. Cortina Gil et al, NA62 Collaboration, *Search for K^+ decays to a muon and invisible particles,* Phys. Let. B 816, 136259 (2021).
- E. Cortina Gil et al, NA62 Collaboration, *Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay,* J. High Energy Phys. 2021, 6 (2021).
- R. Aliberti et al, NA62 Collaboration, *Search for lepton number and flavour violation in K^+ and π^0 decays*, Phys. Rev. Lett. 127, 131802 (2021).
- S. Ghinescu, B. Döbrich, E. Minucci, T. Spadaro, *A biased MC for muon production for beam-dump experiments,* Eur. Phys. C 81, 767 (2021).

5.2 Talks:

- *HASC upgrade status*, NA62 weekly meeting, 14 January 2021.
- *Background in Beamdump from MC*, NA62 Exotics WG meeting, 04 February 2021.
- *HASC 2021 implementation*, NA62 Software WG meeting, 09 March 2021.
- *Beamdump background Data vs MC*, NA62 MC Validation WG meeting, 10 March 2021.
- *Background in Beamdump*, NA62 Exotics WG meeting, 11 March 2021.
- *Update on beam-dump background*, NA62 Exotics WG meeting, 22 April 2021.
- *HASC Status*, NA62 Run Meeting, 28 July 2021.
- *General update and ALP $\to \gamma\gamma$ update*, NA62 Exotics WG meeting, 02 September 2021.

6. Further group activities (1 page)

- Collaborations, local synergies

The multifunction rack control unit (MRCU) hardware was developed and built in the framework of NUCLEU 16 42 01 03 Project. The MRCU firmware and the high-level software were developed in the framework of the present project, the MRCU unit being operated at CERN ECN3 since July 2016 being part of the HASC Control system.

The MRCU will be included in the PANDA Controls Technical Design Report, to be published in 2020, as the solution to control the electronics racks used by PANDA Experiment at FAIR (Darmstadt).

7. Budget request for the next year

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	Type of expenditures	**2022**
1	**PERSONNEL EXPENDITURES, from which:**	**546,444.00**
	1.1. wages and similar income, according to the law	534,420.00
	1.2. contributions related to salaries and assimilated incomes	12,024.00
2	**LOGISTICS EXPENDITURES, from which:**	**219,500.00**
	2.1. capital expenditures	100,000.00
	2.2. stocks expenditures	50,000.00
	2.3. expenditure on services performed by third parties (including the contribution to CERN)	69,500.00
3	**TRAVEL EXPENDITURES**	**80,000.00**
4	**INDIRECT EXPENDITURES – (OVERHEADS) ***	**318,722.00**
	TOTAL EXPENDITURES (1+2+3+4)	**1,164,666.00**
	Indirect Expenditures = General IFIN-HH Overheads (35% from 1+ 2.2 +3) + Particle Physics Department Overheads 15 % from 1	

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[3] M. Bordone, D. Buttazzo, G. Isidori and J. Monnard, Eur. Phys. J. C 77 (2017) 618
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