Study of rare kaon decays at the CERN SPS (NA62)
- 2020 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	Technician –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 scalar decay channels and exclusion capabilities. 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:

- Concluded the operational test of the new HASC modules with cosmic rays. The remaining untested four (4) modules are functional;
- Developed a method to calibrate the HASC with cosmic rays muons and to implement HASC digitization in NA62 MC;
- Performed, at the request of the collaboration, a thorough study dedicated to understanding the reason for HASC's efficiency as a photon veto. Aside from the event topology, this study revealed also the optimal placement for the new HASC modules.

The work for the high accuracy determination of NA62 sensitivity to Higgs mixed dark scalar singlet portal has been continued.

We have implemented 3 variance reduction techniques in the official NA62 Monte Carlo software, enabling the $ALP \to \gamma\gamma$ search to achieve enough statistics for background studies.

2. Scientific goals (2 pages)

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

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

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 $K^+ \to l^+ \nu$ 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 $K^+ \to \pi^+ \nu \bar{\nu}$ events, and to keep the total systematic uncertainty small. Assuming a 10% signal acceptance and a $K^+ \to \pi^+ \nu \bar{\nu}$ 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 $m^2_{miss} := (P_K - P_\pi)^2$ 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^+.

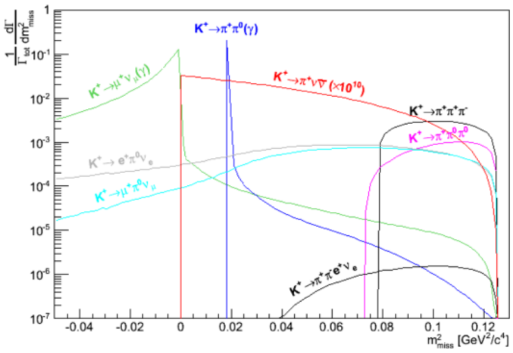

Figure 1: Squared missing mass distribution

2.1 NA62 Hadron Sampling Calorimeter (HASC)

The NA62 experimental setup proposed in the Technical Design Document (NA62-10-07) was improved, by the IFIN-HH team, with a new hadron calorimeter to veto the $K^+ \to \pi^+ \pi^+ \pi^-$ 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.

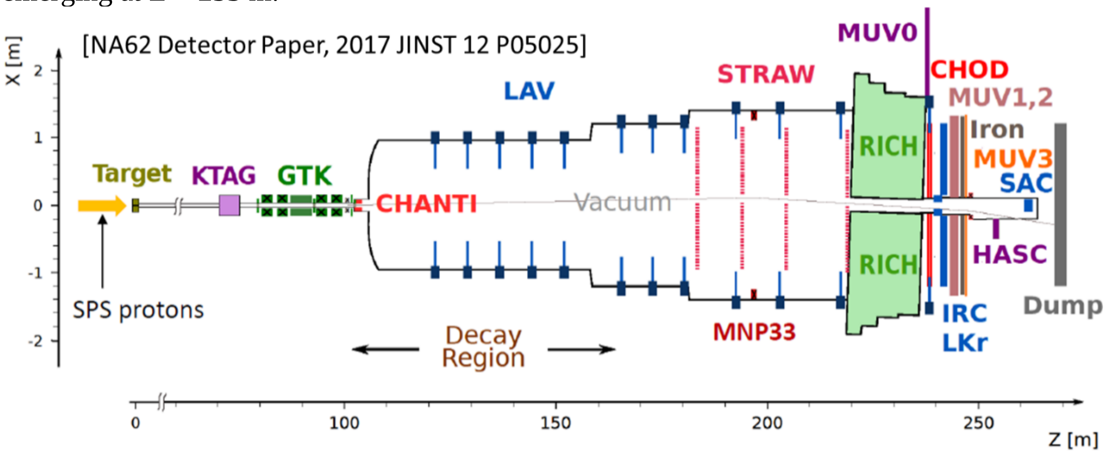

Figure 2: NA62 Experimental setup

The HASC 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.

Using the data coming from the upstream detectors (fig. 2) to select the $K^+ \to \pi^+\pi^+\pi^-$ decays, namely the CEDAR and GTK for K+ identification and the STRAW together with RICH, CHOD and MUV to identify the π^+, π^- pair, HASC data analysis has to spotlight on the π^+ from the positive charged particles beam 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.

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 very actively involved in the study of dark matter in scalar portal [6] which assumes that a new particle (the dark scalar) is mixing with the Higgs SM particle leading to visible final states decays.

The main steps our team will take in the study of this model are:

- Implement the full algorithm in the official NA62 framework (NA62MC) to estimate the sensitivity of NA62 with a visible final state of the dark scalar (e.g. μμ ππ);
- Analyze real data collected by NA62 up to the end of 2018.

Given the experience from 2020 and the growing number of demands, our team will develop and implement various variance reduction techniques (biasing) which will be used in Beyond Standard Model searches as well as in the Precision Measurements working group. For example, for the accurate measurement of the branching ratio of $K^+ \to \pi^+\mu^+\mu^-$, an important background source is the $K^+ \to \pi^+\pi^+\pi^-$ decay with one pion decay in the fiducial volume and another pion decay in the MNP33 Straw magnet, which could benefit tremendously from our work. Another immediate use of biasing techniques is in the Scalar studies done by our team. Muons from early pion decays in $K^+ \to \pi^+\pi^+\pi^-$ events could contaminate the signal, but the kinematical range of the most important contribution is very narrow, thus suitable for biasing.

3. Scientific achievements in the last three years corresponding to the actual program funding (2 pages)

During the period 2018-2020, our group's efforts were focused on two directions: one being dedicated to the HASC subdetector (evaluation of performances and studies on upgrade), while the other regards the participation in the Exotics working group physics programme.

HASC detector performance in terms of time resolution is shown in Fig. 4, where the time difference between the K^+ detected by KTAG (CEDAR) and the HASC π^+candidate is displayed. Using ToT information, the charge deposited by the π^+ candidate, Fig. 5, is calculated. Compared with the charge calculated using muon calibration runs, a fairly good separation pion-muon is obtained by applying a cut at about 100 pC.

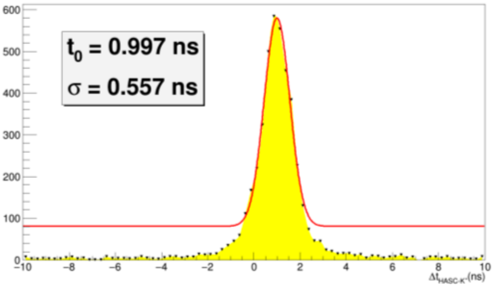

Fig. 4: HASC – KTAG time difference

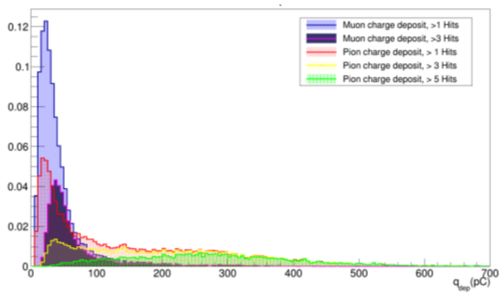

Fig. 5: HASC energy deposit comparison

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. 6) produced in γ pair production. The simulation result 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.

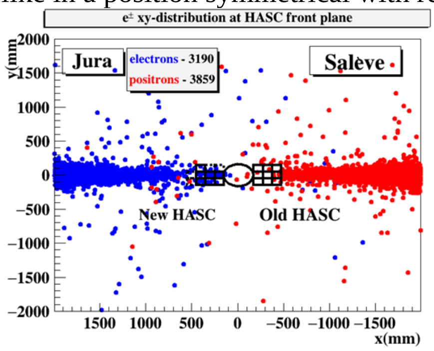

Fig. 6: e^+ e^- distribution at HASC front plane

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 . 5 out of the 9 new HASC modules where tested in IFIN-HH with cosmic rays (Fig. 7), by employing a TDC triggered whenever a HASC section was hit.

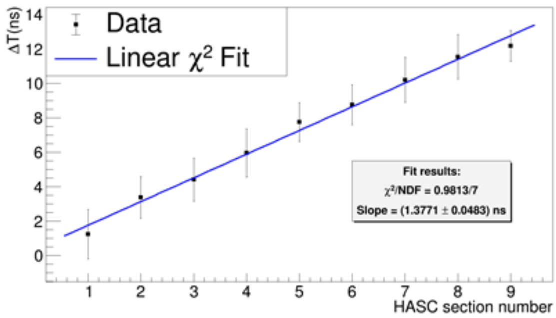

Fig. 7: TOF between succesive HASC sections

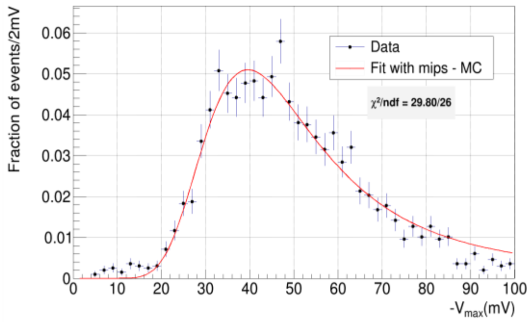

Fig. 8: Signal amplitude / section when all 10 sections are hit

In the following year we continued the testing of new HASC modules, this time employing a 5 GS /s, 12 bit digitizer. Fig.8 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.

The cosmic rays tests revealed that all 9 (new) HASC modules are functional and the new mechanical structure and SiPM FEE are performing very well. Therefore, we are taking into account to upgrade also the "old" HASC modules with the new mechanics and electronics. - SARS-COV-2 evolution in 2021 may have consequences on upgrade timing.

Our contribution to the Exotics working group in 2019 was the completion of a Toy MC tool for the study NA62 sensitivity to the Higgs-mixed dark scalar (S) in the singlet portal including the secondary 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[7]). 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).

Then, 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 rate 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. 9 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.

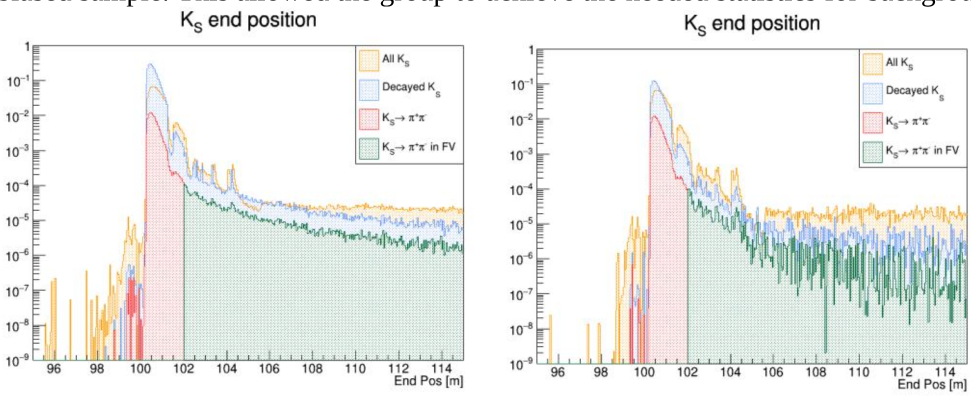

Fig. 9 Decay Z-coordinate of K_S mesons in the biased (left) and standard (right) MC productions

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 $10^{16} POT$.

Thanks to our efforts, we were included on the list of authors of the internal note that will be published in the next few months. This note will also become a full-fledged ISI publication in one of the most interesting subjects of Beyond Standard Model physics.

During the last months, several analysis groups expressed their interest in developing biasing schemes for their particular cases. This will be one of the main activities within our group in the future, allowing us to contribute to multiple physics topics within the collaboration.

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.	
Stefan-Alexandru GHINESCU	Data analysis, MC simulation and reconstruction software	
Ovidiu-Emanuel HUTANU	HASC upgrade, maintenance and operation;	
Petre-Constantin BOBOC	Data analysis	
Neagu IONEL	HASC upgrade and maintenance	
Alina MOTORGA	Project accountant	

- 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

- *Searches for heavy neutral lepton production in K^+decays to positrons*, E.Cortina Gil et al, NA62 Collaboration, Phys. Lett. B 807 (2020) 135599;
- *An investigation of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay*, E.Cortina Gil et al, NA62 Collaboration, arXiv:2007.08218 , accepted for publication in Journal of High Energy Physics;
- *Searches for exotics decays with NA62*, PHENO 2020, Pittsburg USA, 05 May 2020;
- *Update on Dark Scalar/FastMC*, NA62 Exotics WG meeting, 03 April 2020;
- *Biasing in (exotic) MC*, NA62 Exotics WG meeting, NA62 Analysis Week, 16 April 2020;
- *HASC studies*, NA62 Weekly meeting, 28 May 2020;
- *Bremsstrahlung biasing*, Exotics WG Meeting,, NA62 Analysis Week, 15 July 2020;
- *Status of ALP $\to \gamma\gamma$*, Exotics WG Meeting, NA62 Analysis Week, 02 September, 2020;
- *Search for di-gamma in beam-dump mode - update*, Exotics WG Meeting, NA62 Analysis Week, 22 October 2020.

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	**2021**
1	**PERSONNEL EXPENDITURES, from which:**	**392,135.00**
	1.1. wages and similar income, according to the law	383,506.00
	1.2. contributions related to salaries and assimilated incomes	8,629.00
2	**LOGISTICS EXPENDITURES, from which:**	**182,997.00**
	2.1. capital expenditures	99,997.00
	2.2. stocks expenditures	20,000.00
	2.3. expenditure on services performed by third parties (including the contribution to CERN)	63,000.00
3	**TRAVEL EXPENDITURES**	**60,000.00**
4	**INDIRECT EXPENDITURES – (OVERHEADS) ***	**267,568.00**
	TOTAL EXPENDITURES (1+2+3+4)	**902,700.00**
	Indirect Expenditures = General IFIN-HH Overheads (35% from 1+ 2.2 +2.3 +3) + Particle Physics Department Overheads (15 % from 1 + 2.2 +2.3 +3)	

Bibliography:

[1] NA62 Collaboration, *Proposal to Measure the Rare Decay $K^+ \to \pi^+ \nu\bar{\nu}$ at the CERN SPS,* , CERN-SPSC-2005-013, 2005.

[2] A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, *$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in the Standard Model: status and perspectives,* J. High Energy Phys. 1511 (2015),33.

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

[4] C. Bobeth and A. J. Buras, J. High Energy Phys. 1802 (2018) 101.

[5] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98 (2018) 030001.

[6] M. Pospelov, *Notes on benchmark models for the PBC evaluation*

[7] H. Dijkstra, T. Ruf, https://cds.cern.ch/record/2115534/files/SHiP-NOTE-2015-009.pdf